# 1663

Extragalactic engines
The FUTURE of reactor materials
Scanning for signs of life
Trustless yet trustworthy proofs
Lighter-than-air solids

Chaos theory.

time travel,

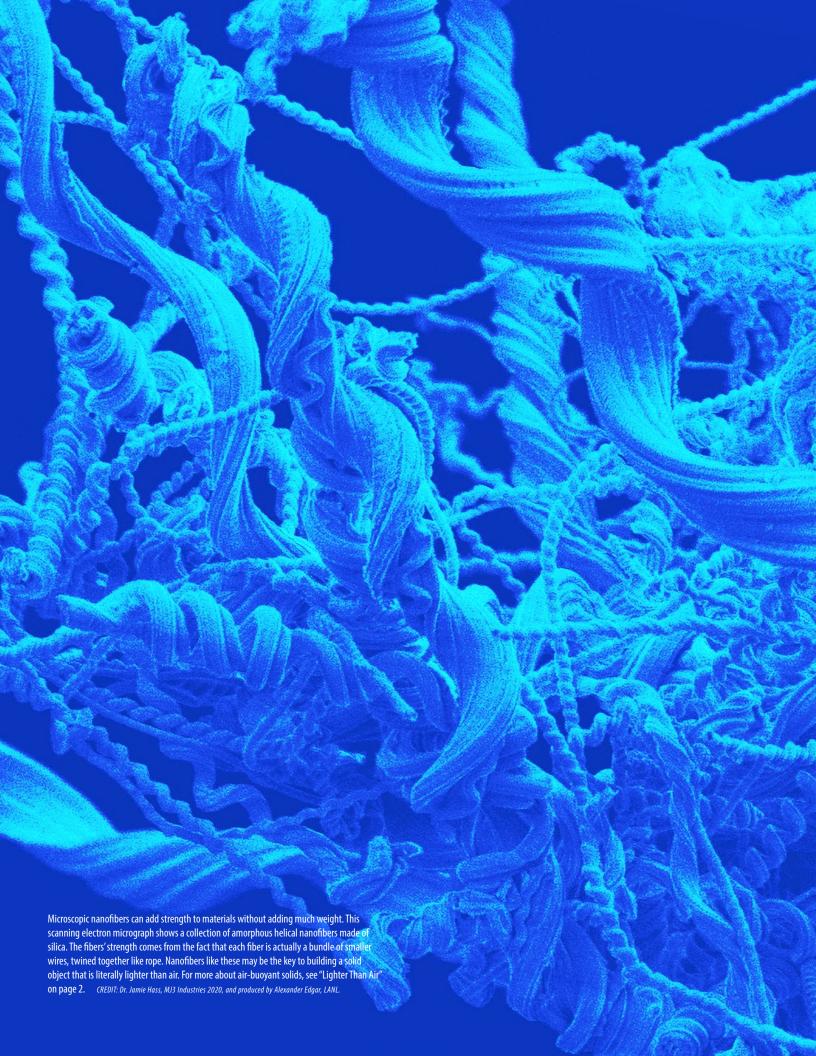
and the

QUANTUM

BUTTERFLY

EFFECT







## LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

#### ABOUT THE COVER

The butterfly effect describes a situation in which a tiny change in some physical system balloons into a tremendous change at a later time. In classical (non-quantum) physics and mathematics, it falls within the domain of chaos theory and expresses the notion that in some complex systems, predicting the future is impossible without perfectly detailed knowledge of the present. For decades, scientists have sought, with limited success, to discover whether there is a subatomic-particle-level, quantum-physics version of chaotic behavior and the butterfly effect. Now Los Alamos research, borrowing upon the quantum-computing concept of "circuit complexity," has revealed that there is indeed a quantum butterfly effect. However, further research showed that a more extreme form of the effect—one brought about by going back in time and making small changes, then allowing the future to unfold differently from there—is actually inhibited by quantum physics. In a sense, quantum information, and the reality it describes, turns out to be self-protective. (The butterfly wing designs shown here are patterned after a standard visualization in chaos theory.)

#### ABOUT OUR NAME

During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

#### ABOUT THE LORD LOGO

Laboratory Directed Research and Development (LDRD) is a competitive internal program by which Los Alamos National Laboratory is authorized by Congress to invest in research and development that is both highly innovative and vital to national interests. Whenever 1663 reports on research that received support from LDRD, this logo appears at the end of the article.

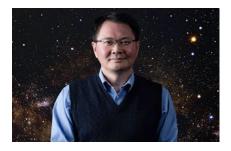
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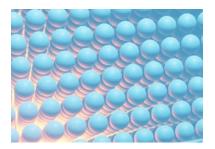


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# SPOT IGHTS

# Lighter Than Air

A solid material able to float in the air could be on the horizon.

In mid-March of 2020, physicist Miles Beaux and chemist Chris Hamilton were in hot pursuit of a harebrained idea, when the coronavirus pandemic forced them to a grinding halt. Their project—to build a solid object that is lighter than air—needed the scientists to fly to Boston to see about having a piece custom built. But then Boston called and said, "Don't come," and then Los Alamos said, "Go work from home," so they went home and started thinking of workarounds.

Beaux doesn't dispute the characterization of "harebrained" for his idea of a solid material that is lighter than air. But that's no reason not to do it. He's encountered naysayers at every turn, and he's kept going, and around each corner, so far, he's found success.

It started with an offhand comment to Hamilton, an aerogel expert, about how aerogels could be the way to build a helium-free air-buoyant balloon. Hamilton suggested a particular aerogel—polyimide, commonly used in the production of electronics and medical supplies—and with that the air-buoyant-solid project was off the ground.

Aerogels only start as gels—they are ultralight liquids that solidify into ultralight solids with high porosity and low density. The first challenge was to make a hollow polyimide sphere and see if it would hold

New materials, specifically aerogels like the polyimide used in this threeinch prototype, may be the key to bring Lana de Terzi's idea within reach.

vacuum. Because the aerogel material itself is heavier than air, the inside of the sphere must be evacuated of air in order for the object's overall density to be light enough.

Beaux explains, "It's like a ship on the ocean surface with pockets full of air, compared to a sunken ship whose pockets have filled with water. Only in our case, with pockets full of air the object sinks—we need pockets full of nothing."

The team produced two three-inch polyimide hemispherical shells, put them together, and evacuated the center chamber, fully expecting one of two things to happen: either air would pass freely through the material, making vacuum impossible, or the vacuum would cause the material to collapse or shatter. But neither happened. The two halves held together with no glue, only the ambient air pressure pushing against the vacuum interior, for nearly a minute. Buoyed by this success, the team doubled down, incrementally decreasing the thickness and optimizing the density of the material until eventually a test sample held vacuum-again without glue-for over 12 hours.

Initially the team used a combination of heat, pressure, and vacuum to solidify the polyimide from liquid to solid, but that method only allowed for up to three-inch diameter prototypes. To build a larger sphere, they had to move to a freeze-drying method which similarly facilitated the state transition, but still maxed out at 11.5 inches. This is the largest the team has achieved so far, but even if it holds vacuum—they are preparing for those tests now—it won't float. That's because it is still not big enough. According to Beaux's calculations they need a sphere of at least

1.4 meters in diameter for the ratio of material to vacuum to be sufficient for liftoff.

Beaux and Hamilton were going to Boston to have the 1.4-meter version made by a private aerogel company. When their trip was canceled because of the pandemic, they started working on in-house ways to make the full-size prototype. Their meantime efforts paid off, and they now have a 1.4-meter hemispheric mold. But it's too big for either the heat-plus-pressure method or the freeze-drying method, so



In 1670, Italian aeronautics pioneer Francesco Lana de Terzi published an idea for a vacuum-balloon-based flying airship. As depicted in this 1909 watercolor postcard, his idea was that by creating a vacuum inside four thin-walled copper spheres, the whole ship would become lighter than the surrounding air. CREDIT: A. Molynk, Courtesy of Science History Institute.

they are presently working on developing a new method.

With large diameters and thin walls, Beaux expects the full-size prototype may need reinforcing. But he's got a plan for that. Beaux's background is in nanomaterials, and he's already demonstrated that the inclusion of helical nanofibers within the polyimide, like microscopic ropes made from silica, can increase the material's strength several hundred times over without weighing it down too much. Like the other hurdles he's cleared so far, Beaux is confident he will clear this one.

Why is Beaux pursuing this? Well, one reason is that helium is a non-renewable resource, and the world is running out. So scientific balloons, party balloons, anything that relies on helium to stay aloft, will need a new way. Another application would be to provide floating, distributed internet to rural locations that presently lack adequate infrastructure. Besides, pursuing harebrained ideas and making them work in the face of doubt has a certain satisfaction all its own. LDRD

-Eleanor Hutterer

#### **ENERGY INNOVATION**

### Power Plant Revamp

New materials and updated models to boost energy infrastructure

Technologies for alternative energy are humming right along, and the power grid gets greener every year. But fossil fuels are still the primary players in the global energy game and will be for decades to come. So important new technologies for those power resources are humming along too.

Traditional coal-burning power plants were built with the best technology of the time—and with a certain lifespan in mind. The predicted lifespans of these facilities were based on continual, nearly steady-state operation to meet all of the nation's energy needs. Now, energy from alternative sources like the sun or wind is meeting some of those needs, so traditional facilities have to adaptramping production down temporarily-to make room in the power grid for the alternatively sourced energy. This ramping up and down strains the system, and can accelerate aging, thus invalidating lifespan predictions. Furthermore, modern methods that improve energy-extraction efficiency create more extreme operating conditions-higher temperatures and pressures—than these facilities were built for.

The industry needs new lifespan predictions for extant facilities, and it needs new facilities built with new materials that have been expressly designed for high-temperature and high-stress environments.

A national effort funded by the U.S. Department of Energy (DOE) Fossil Energy program called

eXtremeMAT (XMAT)

is addressing

both of these challenges by harnessing the expertise and capabilities within the national laboratory complex. A large part of XMAT is computation—modeling and simulating a material's microstructure to predict how it will change with age—and Los Alamos is a key contributor on that front.

The discovery of new materials has historically been slow because it is Edisonian, that is, pure trial and error. Los Alamos scientists are using state-of-the-art computational methods, like physics-based machine learning, to considerably reduce the iteration and accelerate the timeline of new material development.

Materials scientist Laurent Capolungo leads the effort at Los Alamos. He explains, "We are developing computational tools and methods to assess the evolution of microstructures in ferritic and austenitic steels—materials that will be subjected to extreme conditions." (Ferritic and austenitic are two kinds of steel alloy that have different physical properties.)

"There are two advances we've made so far," Capolungo continues. "First, we've developed models that are sensitive to the material's microstructure and its thermomechanical processing history to predict the material's rupture life. Second, we've developed very sophisticated surrogatematerial models for engineering applications that are highly accurate but also simple enough to be user friendly."

Both kinds of models—the lifetime predictors and the material evaluators—will provide a science-based understanding of the relationship between a material's microstructure and its performance. This information will be used by collaborating XMAT scientists to physically produce and test candidate new materials.

One reason why Los Alamos is so well positioned to take on much of the

When a material undergoes prolonged exposure to extreme conditions, microstructural damage will accumulate. This simulation, produced at Los Alamos for the eXtremeMAT program, shows a naturally occurring void (yellow sphere) within a sample of iron, which can behave as a starting point for microstructural damage. Dislocations on different slip systems (crystallographic planes within the material) are indicated by lines of different colors. The simulation shows that damage is intimately related to those dislocations.

CREDIT: M. Orondo and A. Kohnert.

computation for XMAT is that some of the leading physics-based tools and models for this type of work were developed at the Laboratory—specifically, the Visco-Plastic Self-Consistent (VPSC) computer code, developed by Capolungo's predecessor and mentor Laboratory fellow Carlos Tomé and Los Alamos scientist Ricardo Lebensohn, and the Elasto-Visco-Plastic Fast Fourier Transform (EVP-FFT) code, developed by Lebensohn. These codes deliver physics-based predictions of a material's lifespan, based on microstructural changes in the material. Although they are open-source and used by materials scientists around the world, because they were invented at Los Alamos, the Laboratory maintains the highest concentration of expertise in their implementation.

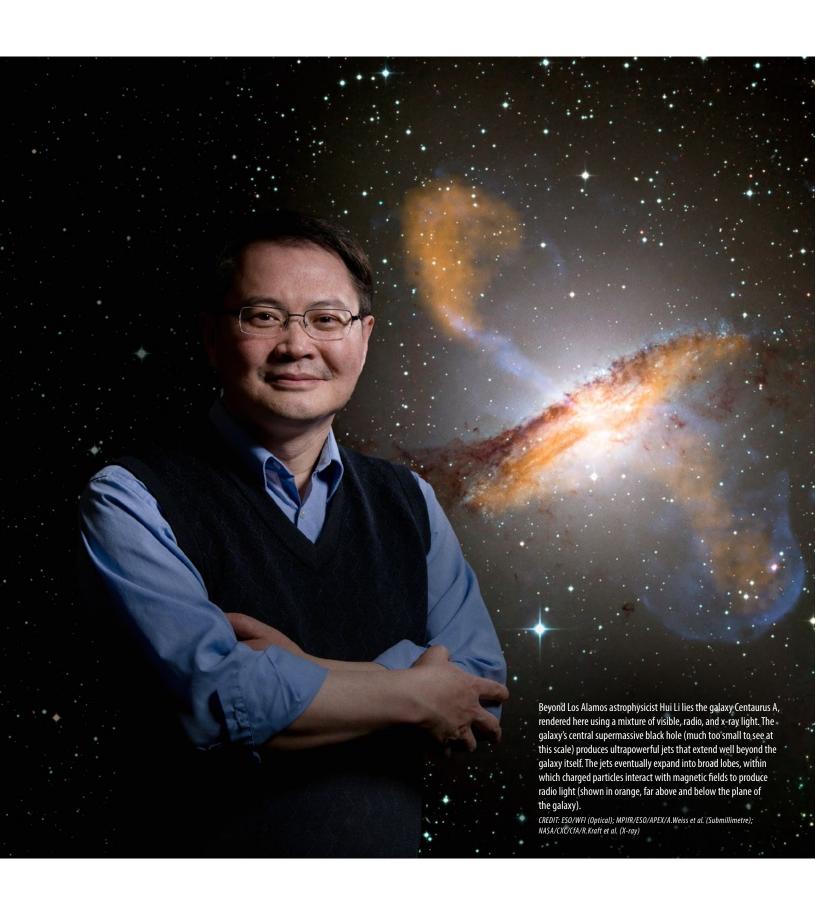
The VPSC and EVP-FFT computer codes were first developed more than 10 years ago with support from DOE's Basic Energy Science and Nuclear Energy programs, as well as the Advanced Simulation and Computing program and the Joint Munitions program. Those investments have continually paid off, even more so now with the highly visible and collaborative XMAT project.

"I think this is a good example of how things at Los Alamos work," says Capolungo. "We are leveraging the institutional knowledge that exists here—the expertise and experience acquired from previous work on DOE programs—to make improvements in the fossil energy arena, and quickly."

The goal of XMAT—to use data science to reduce the time and cost for alloy development and lifetime prediction—is ambitious. But the tools needed to meet this goal—data mining, machine learning, multiscale modeling—are Los Alamos specialties. By bringing together experts from across the national laboratory complex, XMAT is improving fossil-energy power systems so that they, and the country, can keep humming right along.

—Eleanor Hutterer

Read more about materials subjected to extreme conditions inside power plants, specifically nuclear reactors, in "When Atoms Get Out of Line" on page 22.





# Hidden Engines of the Cosmos

Astrophysicist **Hui Li** leverages Los Alamos's unique strengths to reveal the secrets of the high-energy universe.

ASTROPHYSICS IS A LAND OF MYSTERIES. Some new discovery is made—a source that's brighter than it should be, or a celestial event that should not have occurred—and astrophysicists like me set out to explain how it came about. It is usually our job to construct a coherent story for what is going on in our universe, explain the unexplained, and resolve the mysteries, all without a single in-situ measurement. Other times it is our job to look at the universe with fresh eyes, and when we do that, we identify new mysteries.

Case in point: Just last year, a new kind of observatory made an unanticipated discovery. Instead of measuring visible light with lenses and mirrors, or measuring radio waves with a big metal dish, the LIGO observatory measures gravitational waves—incredibly faint ripples in the fabric of spacetime—with exquisitely sensitive laser-based instrumentation in kilometers-long ultrahigh-vacuum tunnels.

These gravitational waves are so weak that the only ones we can hope to see are created by extraordinary gravitational events, such as two black holes colliding. This happens from time to time. One such collision witnessed by LIGO last year involved the merger of two black holes with masses estimated at 66 and 85 times that of the sun. According to wellestablished theory, however, the process by which black holes form should max out around 50 solar masses. So where did these two come from?

Or consider another detection at the IceCube Neutrino Observatory, a collection of detectors spanning a cubic kilometer embedded inside ice beneath the South Pole. IceCube watches for a faint, telltale flash of visible light that can, on rare occasion, result from a neutrino particle passing through the earth. In the past eight years, the observatory has documented numerous neutrinos with energies ranging up to about a billion



(Above) The supermassive black holes that live at the centers of galaxies are often surrounded by a great deal of gas and dust, which settles into an accretion disk. The disk strongly winds up magnetic field lines to produce a jet of matter blasting from over the poles of the black hole. Such jets are evident in many telescope observations, such as those represented on the previous page. (Right) Simulations by Li and colleagues reveal how the jet structure emerges. Colors indicate variations in pressure (and arrows indicate gas velocity); red zones show where high exterior pressure helps maintain a narrow jet (vertical column), beyond which the jet expands into large swaths of intergalactic space (gray lobes).

CREDIT: (Left) Robert Hurt/NASA JPL-Caltech

times greater than the most energetic neutrinos ever seen before, which themselves came from a massive supernova. So what's producing these wildly energetic neutrinos? What celestial power source could dwarf a supernova by a factor of a billion?

You know you're in a fascinating line of work when progress means not only resolving mysteries like these but also creating them with some new kind of observation. Personally, I tend toward the former. I try to figure out how things work and resolve the mysteries that new observatories identify (and ideally make some predictions along the way). But nowadays, astrophysical mysteries are rarely resolved by a clean, straightforward idea that can be expressed with a single, textbook-style equation. Today's mysteries tend to involve a great deal of complexity and require interdisciplinary approaches. I am fortunate to have developed expertise in complex, magnetized plasma systems, based on advances in theory, numerical simulation, and laboratory experiments. It has frequently meant that I can see my way to a possible solution to some high-energy mystery—including to the two I just mentioned. But we'll come back to those after a little background.

#### Underappreciated magnetism

Relatively early in my 26-year career (so far) at Los Alamos, I had the privilege of working with a giant in the fields of astrophysics and plasma physics, Stirling Colgate. Stirling was part of what I think of as an earlier generation of scientists with the heart to tackle big, fascinating problems in science and do it without worrying about funding. It took guts, foresight, and an appreciation of the big picture to make a career doing that kind of work—a strong "let's see where this takes us" spirit. (To be fair, he also worked prolifically on practical problems, such as

thermonuclear weapons, satellite-based detection of nuclear detonations, and other innovative fusion research.)

So I try to maintain this entrepreneurial spirit, exploring the frontiers wherever they may lie—doing my part to keep Los Alamos nimble and its research pioneering. One such line of research that I have long pursued centers on a class of objects called supermassive black holes. They live at the centers of large galaxies, including ours, and, despite being as massive as millions or billions of suns, are only a fraction of the size of our solar system.

If one were to ask what are the ultimate hidden engines that drive most of the high-energy phenomena throughout the cosmos, supermassive black holes rank at the top. How can such comparatively tiny objects (tiny in size but huge in mass) be so important? Back in the late 90s, we developed a perspective on supermassive black holes and the universe that was not widely accepted at the time but has since come to be better supported: that magnetized jets are responsible for drawing energy from supermassive black holes and distributing it around intergalactic space—the sprawling space between galaxies—where it exists as the lion's share of all energy present. (A plasma is a gas that is hot enough that electrons have been stripped off of their atoms, resulting in the particles that make up the gas being electrically charged—ions and electrons—unlike the neutral atoms that make up a lower-temperature gas, such as air. By virtue of being charged particles, plasmas interact strongly with magnetic fields.)

Supermassive black holes are pretty quiet in the universe today. But earlier in the history of the universe, they were screaming. There was an ample supply of gas surrounding a supermassive black hole, and as that gas was drawn in, it would speed up, with faster and faster particles colliding to generate a tremendous amount of heat. Meanwhile, these particles start orbiting around the black hole and settle into a flattened geometry

called an accretion disk (their last resort to save themselves from black holes). There are two eventual outcomes. First, the accretion disk is heated dramatically, producing an extraordinarily bright glow—a glow we often refer to as a "quasar" (quasi-star). Second, the magnetic fields are reconfigured by the black hole and accretion disk in such a way that these fields store the black hole's energy and blast away as jets (with some of the disk material mixed in) over the poles of the black hole. These jets, billions or

and I determined that large galaxy clusters—groupings of thousands of galaxies all orbiting around each other—are the primary dumpsites for most of the energy from supermassive black holes. About twenty years ago, we began conducting extensive MHD studies on the structure of jets, and it turns out that

# The touch of supermassive black holes can be felt absolutely everywhere, including here on Earth.

trillions of times longer than the diameter of the black hole itself, act as intergalactic conveyor belts, sharing the black hole's energy across the colossal scales of intergalactic space.

There's something I find delightful in all this. Supermassive black holes are extraordinary power sources. The gravitational energy released by their formation and growth (as they consume matter falling in) is enormous. But together with being extraordinarily powerful, they are extraordinarily compact. One might naively expect that their impacts should only be felt in their immediate vicinities. Yet through the rich and complex dynamics of magnetically active plasmas, an amazing, self-organized structure emerges, namely, an astrophysical jet. As a result, the touch of supermassive black holes can be felt absolutely everywhere, including here on Earth.

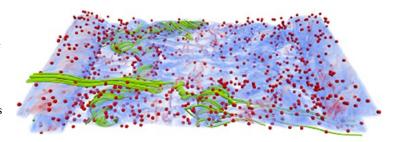
We showed that over time, even after the supermassive black hole has consumed all the available gas and therefore gone quiet, the residual magnetic energy from the former jets would continue to spread throughout intergalactic space, filling up the volume in between massive galaxies. Quite interestingly, these jets are also believed to produce high-energy particles that zoom every which way across the universe and periodically streak through the earth's atmosphere, raining down on us harmlessly (thanks to the earth's precious atmosphere and magnetic fields) in the form of ultrahigh-energy cosmic rays.

#### A jet all the way

Like much of my research over the past 25 years, learning to understand supermassive black hole jets has relied upon detailed studies of turbulent magnetohydrodynamics (MHD) in the relativistic regime (in which particles are so energetic as to move at nearly the speed of light). This is exceptionally complicated, but it's something of an historical specialty here at Los Alamos, since aspects of it are necessary in the study of the dynamics of fusion and nuclear detonations. (Manhattan Project-era giants, such as Fermi and Rosenbluth, were founding fathers of this field.) We have supercomputer codes designed to simulate the MHD and kinetic action of plasmas, and my colleagues and I have adapted and expanded these for astrophysical settings. Our computations and supercomputer simulations have shown that complex magnetic effects often dominate the dynamics of high-energy astrophysical systems.

There are two main dumpsites for black hole energy along a jet, each of which engenders exotic phenomena. My colleagues

different magnetic field components conspire to maintain a tight, narrow helix structure (much like a slinky) over a long distance as the jet pushes through the interstellar gas within its host galaxy. A shock wave helps to harden the leading edge of the jet, preventing it from splaying out until the interstellar gas thins to the point where the pressure support is mostly gone. Then the jet spreads out into broad lobes, seeding the intra-cluster medium and the intergalactic medium with magnetism.



Zooming in on a minuscule segment of a magnetized plasma jet, as simulated by Los Alamos's Trinity supercomputer, reveals complex bending, kinking, and reconnecting of magnetic field lines (shown in green). Kinking eventually leads to field lines breaking and reconnecting, which produces tremendous particle acceleration within the jet and therefore explains the long-mysterious origin of observed ultrahigh-energy cosmic rays and neutrinos. The red dots represent energetic particles that have been efficiently distributed within the simulated volume by self-generated turbulence and greatly accelerated by magnetic forces.

One key signature we demonstrated is how the turbulent (erratic, clumpy) gas motion inside the clusters can sustain and amplify the magnetic fields. We further showed that the dissipation of this magnetic energy helps maintain the cluster's thermal energy, thereby resolving a longstanding mystery about how hot x-ray-emitting gas within galaxy clusters continues to glow long after it should have cooled: it is continuously recharged by turbulence-enhanced magnetic energy, seeded by supermassive black hole jets.

However, jets are imperfect conveyor belts for carrying black hole energy to great distances. The other dumpsite—and in some ways the more exotic one—is actually within the first one-millionth of the conveyor belt's length. Here, dazzling flares of intense radiation, high-energy particles, and neutrinos are produced suddenly. Magnetic field lines within the jet are bent to the point of kinking, forcing the lines to reorganize, reconnect, and convert magnetic energy into motion, as well as greatly accelerate charged particles. In fact, when the Trinity supercomputer was first brought to Los Alamos in 2017, we were fortunate to be part of a team that took it for a test drive. With it, we demonstrated that particles in magnetized jets can indeed be accelerated and obtain a distinctive velocity distribution—not the usual thermal distribution associated with glowing objects like stars—which helps to explain the energy spectrum that has long been observed in jet-driven astrophysical systems (which also include x-ray-emitting binary star systems and gamma-ray bursts).

One telltale sign of magnetically regulated processes is the polarization of emissions made by energetic particles in the magnetic field. Gyration of these particles around magnetic fields causes the emission in the direction perpendicular to the

telescopes, all coordinating to converge on a single, coherent explanation of what is really going on in ultra-energetic systems.

That brings me back to the latest messenger in the modern era of multi-messenger astronomy: gravitational waves. When LIGO recently published a new discovery about the merger of two stellar-mass black holes (each with the mass of a large star, not millions or billions of stars' worth like the supermassive black holes I've been talking about), and it sparked the mystery of how these black holes got to be bigger than the 50-solar-mass limit their formation mechanism should have imposed, I got very excited. My studies of supermassive black hole disks had previously led me to examine planet-forming disks around young stars and the conditions that allow planet embryos to survive and migrate within a disk, despite the drag the disk matter could impose [see "Wandering Worlds" in the March 2011 issue of 1663]. I realized that the same conditions could well be present in the accretion disk around a supermassive black hole.

The idea is that stars, even binary stars—and even dead binary stars that have collapsed into black holes—could have formed, lived, and died within the supermassive black hole's accretion disk. And the binary black hole system LIGO detected has approximately the same mass ratio relative to the supermassive black

# There are two main dumpsites for black hole energy along a jet, each of which engenders exotic phenomena.

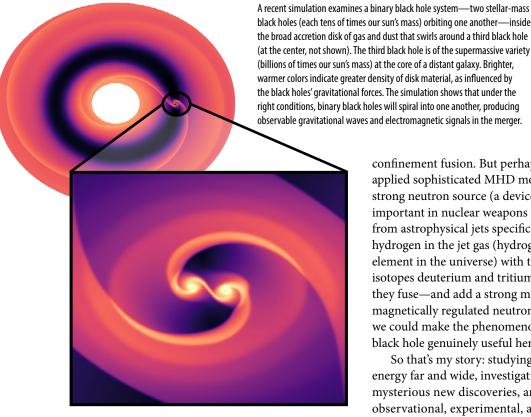
magnetic field to be different from that in the parallel direction. To test our models, we were compelled to integrate three distinct components together: how relativistic jets emanate from supermassive black holes, how the particles get accelerated in such jets, and what radiation they produce. We got quite excited when we found that large changes in polarization behavior (which are most naturally explained in strongly magnetized conditions) could be generated during flares, a puzzling fact that had been reported by observations.

Speaking of resolving mysteries, remember I mentioned that a current mystery is the origin of the wildly energetic neutrino particles detected by the IceCube observatory at the South Pole? Well: a 2017 neutrino detection happened to be coincident with radio and gamma-ray signals seen by other observatories, corresponding to an energetic flare from a "blazar"—a distant supermassive black hole jet that happens to be pointing toward us (i.e., a quasar that's oriented just-so). This suggested that particle acceleration within the jet might be responsible for generating the mysterious neutrinos, probably via a known mechanism by which high-energy protons immersed in an electromagnetic glow (radio waves, visible light, etc.) can undergo particle-physics reactions that result in neutrinos.

My colleagues and I studied the event and explained how the magnetic forces and plasma dynamics within the jet could lead to sufficiently energetic neutrinos and even how the fine details of the necessary proton acceleration within the jets could be resolved with upcoming observational studies. This research is particularly exciting because it capitalizes on "multi-messenger" observations: neutrino telescopes, radio telescopes, x-ray and gamma-ray

hole it orbits as that of the earth relative to the sun: an intriguing commonality for these two wildly different systems. Thus, the LIGO system, unlike black-hole binaries people normally think of, could live inside a dense disk of material. So even if its black holes were born with less than 50 solar masses as theory demands, they've had plenty of nearby disk material to eat and have thus gained weight. Meanwhile, in a new publication this year, my colleagues and I were able to demonstrate that a narrow subset of binary black holes will indeed be driven to merge within an accretion disk (while the rest will tend to spin apart). It now seems to me exceedingly likely that this is the answer to the LIGO mystery. Even more interesting, the distinctive prediction of this scenario is that such mergers, due to the surrounding disk material present, will involve their own disks and jets and therefore emit concurrent, observable electromagnetic signals (in addition to gravitational waves), while models of isolated black-hole binaries said no such electromagnetic signatures should exist.

I like this LIGO story a lot, and I'm fortunate to be able to say it's just the most recent in a long line of similar stories I've been involved with over the course of my career. It illustrates something I continuously strive for: recognizing interesting and unexpected possibilities within the emerging scientific theory, simulation, experimentation, and observation. We can now detect energetic phenomena *inside* the accretion disk of a supermassive black hole in some distant galaxy. And with upcoming multi-messenger observations that allow gravitational waves to be paired with simultaneous telescope observations—visible light or x-rays, for example—the combined signals will reveal details of jets and



other high-energy processes at work in the very inner cores of the hidden engines of the universe. For my part, seizing on the possibility that the LIGO binary black-hole merger took place within the magnetized plasma of a much larger black hole's accretion disk, and working out how it might have played out in detail, is the kind of sleuthing I find deeply satisfying.

#### **Bringing it home**

Astrophysics is notorious for being pure research, rather than applied research. Often, applied physics discoveries (such as the properties of nuclear reactions) provide valuable information about what is going on in astrophysical settings, but astrophysics research repays that debt by stretching the parameters to extremes and challenging us to think deeper. And even with the help of applied physics, you still can't deliberately adjust the settings on a galaxy or a star; you can only try to find one that seems to be already doing what you're looking for. However, I make a concerted effort to bridge the divide between pure astrophysical research and applied physics and have had some success there.

For example, my collaborators and I conducted MHD studies specifically to help connect astrophysical phenomena with major plasma physics facilities. We demonstrated a number of key parallels between theoretical simulations and experimental outcomes at a plasma-jet experiment at Caltech, and we correlated the astrophysical turbulent magnetic dynamo—the mechanism I mentioned that's responsible for strengthening magnetic fields in galaxy clusters—with the Omega Laser Facility at the University of Rochester. In each case, we made a class of astrophysical research accessible to controlled laboratory experimentation.

As for repaying the debt to applied physics, magnetohydrodynamically complex plasmas are important from a technological perspective, especially in nuclear-fusion research. We have

black holes (each tens of times our sun's mass) orbiting one another—inside conducted multiple studies the broad accretion disk of gas and dust that swirls around a third black hole using the MHD simulation (at the center, not shown). The third black hole is of the supermassive variety (billions of times our sun's mass) at the core of a distant galaxy. Brighter, capability we developed for warmer colors indicate greater density of disk material, as influenced by astrophysical research to the black holes' gravitational forces. The simulation shows that under the help inform plasma physics right conditions, binary black holes will spiral into one another, producing generally, including an observable gravitational waves and electromagnetic signals in the merger. important subset of energy research known as inertial-

> confinement fusion. But perhaps my favorite example: We applied sophisticated MHD modeling to the problem of making a strong neutron source (a device called a Dense Plasma Focus) important in nuclear weapons research—by drawing inspiration from astrophysical jets specifically. If you replace the ordinary hydrogen in the jet gas (hydrogen being the most abundant element in the universe) with the more reactive hydrogen isotopes deuterium and tritium—which produce neutrons when they fuse—and add a strong magnetic field, you get a powerful, magnetically regulated neutron source. Who would have thought we could make the phenomenology of a distant supermassive black hole genuinely useful here on Earth?

> So that's my story: studying the power of magnetism to carry energy far and wide, investigating the ways this power can explain mysterious new discoveries, and grounding it all in rigorous observational, experimental, and even technological science. Honestly, all that is a tall order for a career in astrophysics, and I couldn't do it on my own. Nor could I do it in a more traditional science job as part of a university faculty. Undeniably, what has made this research path possible is the breadth of talent and resources available to me here at Los Alamos. Outstanding colleagues across divisions—experts in astrophysics, plasma physics, turbulence, high-performance computing, and experiments—and access to world-class supercomputers have made it possible for me to do what I do.

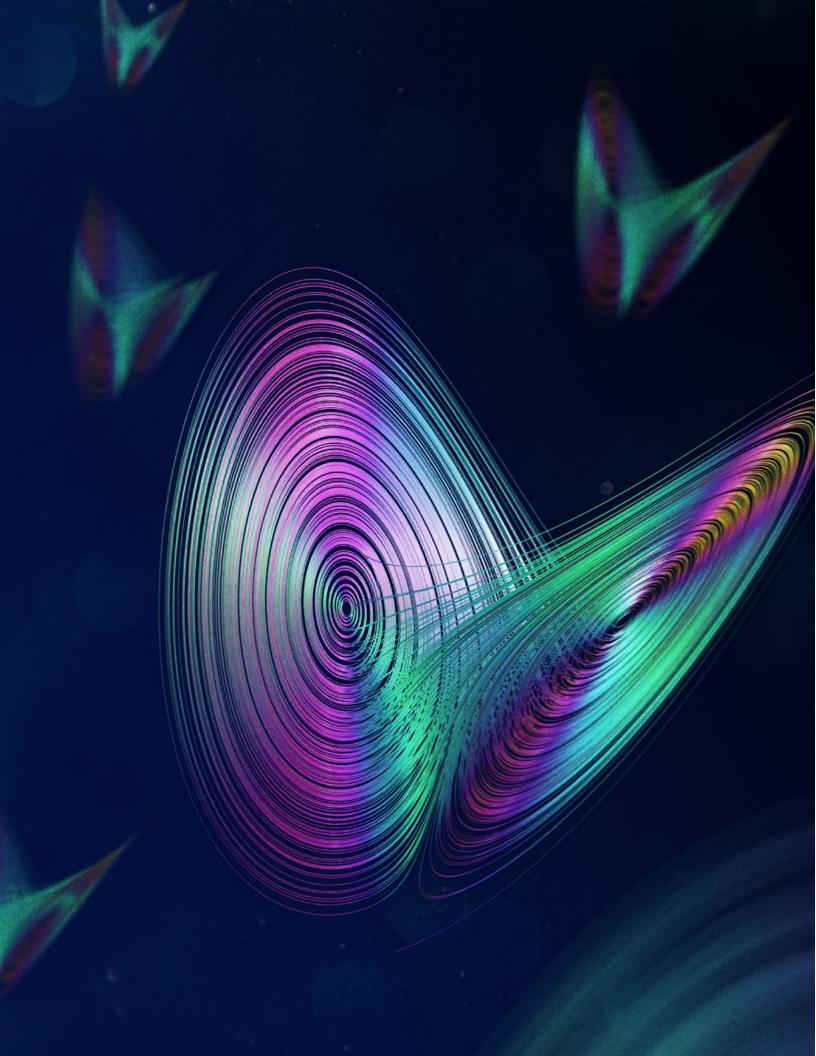
> In a way, we are all energized by powerful ideas. We allow them to interact and grow within the turbulent jumble of theories and observations swirling around. Couple these ideas with the talent and inspiration of my mentors, and particularly all the students, postdoctoral researchers, and scientific staff I've had the privilege to collaborate with in my Los Alamos career, and we massively extend their reach into the broader scientific enterprise, eroding the mysteries that continue to emerge. LDRD

—Ниі Li

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# THE

# QUANTUM

# BUTTERFLY

# EFFECT

At the intersection of quantum physics, time travel, and chaos theory, nothing is simple or straightforward—except the result.

LAST YEAR, AS THE IMPACT OF ONE TINY VIRUS RIPPLED ACROSS THE ENTIRE WORLD and upended virtually every facet of human civilization,
Los Alamos scientists discovered that quantum-level disruptions, rippling across time, do *not* spiral out of control. According to the scientists' simulations, one can take a particle in a specific quantum state back in time and deliberately modify its state in the past without significantly changing it in the present. Voilà: the butterfly effect—in which tiny changes progress into enormous ones—is thwarted at the quantum level.

"It's a little more complicated than that," groans Los Alamos physicist Bin Yan. "For starters," he says, "there's more than one way to construe the butterfly effect."

Indeed there is. Sixty years ago, MIT Professor Edward Lorenz was running a weather simulation and rounded off one of the parameters from six decimal places to three. To his surprise, two months of simulated weather were completely different as a result. He would later liken the situation to the flap of a butterfly's wings spawning a distant tornado. That's the butterfly effect most often mentioned; it's an expression of chaotic behavior. In complex systems such as the weather, a small change in the conditions at one moment can produce an enormous subsequent change overall.

But an earlier version of the butterfly effect derives from the 1955 short story *A Sound of Thunder* by Ray Bradbury. In it (spoiler alert), a man time-travels back to dinosaur times and accidentally steps on a butterfly. When he returns to the present, everything has changed: people's attitudes

Lorenz version of the butterfly effect:
For a sufficiently complex system, a small change in the present quickly balloons into a large change in the future. Lorenz's example was a butterfly flapping its wings in Brazil subsequently producing a tornado in Texas. Los Alamos research demonstrated that quantum systems can do the same, such that a slight change in initial conditions can cause a quantum wave function to diverge wildly with time.

that accurately predicting the weather more than two or three weeks out will always be impossible, for precisely this reason.) Bradbury tells a story that's more timeline sensitivity than chaos—small changes being amplified in modest increments over the long haul, like biological evolution—and, technically, involves a backwards-in-time operation.

Ever the overachiever, Yan worked out the quantum analogues of both.

#### **Quantum chaos**

"At the outset, it wasn't clear that quantum chaos would even exist," says Yan. "The equations of quantum physics give no immediate indication of it."

# At the outset, it wasn't clear that quantum chaos would even exist.

are different, words are misspelled, and a different candidate has won the recent presidential election.

Yan's point is this: the two butterfly effects are related but differ somewhat in character. Lorenz tells a story of chaotic behavior, of small causes producing big effects due to the complexity of the system. Such things can evolve fairly quickly. (Indeed, some scientists argue

In classical (nonquantum) physics, objects can be treated as a collection of point particles in distinct locations with distinct states of motion. Yet despite such a rigid description of

reality, there are times when chaotic behavior readily emerges. Even a small number of simple objects can be assembled in such a way that small changes in the initial setup lead to wildly varying outcomes. A common example is a frictionless pendulum made from two equal-length rods joined by a hinge, similar to a human arm (although in the case of the pendulum, its "elbow" may freely hyperextend). Where a single-rod pendulum released from a horizontal position would swing back and forth repeatedly along the same semicircular arc, a double-rod pendulum would flail about in an enormously complicated fashion, folding and

unfolding as it swings and sometimes windmilling its lower arm full-circle around its elbow. If it were released from a slightly different height or with its elbow ever-so-slightly bent one way or the other, the sequence of motion would be entirely different.

But unlike classical physics, the quantum description of reality does not specify discrete objects at distinct locations with exact states of motion. The basic "object" is not generally a solid entity but rather a diffuse type of particle imbued with certain wave quantity gained a great deal of attention within the research community: the out-of-time-order correlator, or OTOC. It examines any two measurable properties of a quantum system (its energy and its rotation, perhaps), but it does so in a scrambled time order. Specifically, it considers measuring one property in the

# The connection among measures of quantum chaos was suggestive. We were closing in on something.

properties. The mathematical description of its state is called a wave function, and according to the equation governing wave functions, a particle in a fixed energy state doesn't change in time. The more general case of numerous particles in a mixture of states makes the math considerably messier, but a key feature remains: because the equation governing the time evolution is linear, small changes in the initial configuration remain small as time passes. There is no obvious provision for the emergence of chaotic behavior.

Studying chaotic behavior in the quantum realm, therefore, has often involved a little cheating. A pristine quantum system (intended to be analogous to something like a frictionless double-rod pendulum, perhaps) is not chaotic on its own, in the sense that a change in initial conditions doesn't generate complex outcomes. But it might become chaotic if one accounts for a non-pristine system. In particular, by acknowledging that a quantum object, such as an atom, can never be fully shielded from its environment—there are always at least a few stray radio waves or magnetic fields or whatnot flitting about, even in the most tightly controlled laboratory—one can introduce some realistic variations into the equation and thereby obtain complex results. About 20 years ago, scientists defined a quantity known as a "Loschmidt echo" to capture the degree to which variations in a system's environment allow for the emergence of such complexity.

But is that really the same thing as chaos? Is it the Lorenz-type butterfly effect?

"In those early studies," Yan explains, "environmental perturbations, and the Loschmidt echoes that quantify their effect, were viewed as a necessary substitute for true chaos. But it was unclear if there was a genuine butterfly effect at work. After all, we weren't taking some tightly controlled system and perturbing its initial conditions; we were perturbing its exposure to the outside world." Even a boring, back-and-forth, single-rod pendulum might exhibit complex behavior if it were being batted around by wind and hail.

#### **Baby butterflies**

As the 21st century progressed, quantum chaos researchers continued to use Loschmidt echoes and other comparable measures to characterize, well, whatever it was that wasn't exactly chaos but wasn't exactly *not* either.

The relationship to Lorenz-type butterflies remained uncertain. Then in 2015 another

present, then mathematically allowing the system to evolve backward in time and measuring the other property in the past, and subsequently returning to the present to assess how different the first property is. Now, quantum measurements normally disturb whatever they're measuring, so if you measure *this* and then *that* and then remeasure *this* again, even



#### **Bradbury version of the butterfly effect:** Time travel is used to effect a small change

in the distant past, and over the long sweep of time, the present is significantly altered. Bradbury described a visitor to dinosaur times accidentally stepping on a butterfly and then returning to a present that had been completely changed. Los Alamos research, however, showed that quantum states can be transported into the past and altered there with minimal impact on the present.



without all the bother of time travel, you generally get a different result the second time. But the OTOC captures a key variation on that effect by including forward and backward evolution in time. Essentially, the OTOC is a measure of the Bradbury-type butterfly effect.

Yan decided to see if he could find a bridge between the two key quantities in the emerging field of quantum chaos, the

# At the quantum scale, reality is self-healing.

Loschmidt echo and the OTOC. He and his Los Alamos colleagues Lukasz Cincio and Wojciech Zurek—(Cincio recently won the IBM Quantum Challenge, while Zurek is widely recognized for foundational research bridging the quantumclassical divide with a theory of quantum decoherence)—set out to see if they could link the two analytically (pencil and paper) or numerically (via computer calculation). As it turned out, they could do both: they found that the two were intrinsically related, that the OTOC could be approximated from the Loshmidt echo. Complex quantum systems, it seemed, had elements of both butterfly effects.

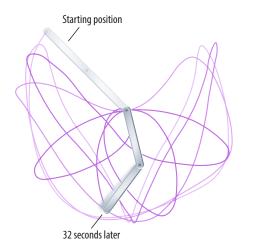
"The connection between OTOC and Loschmidt echo—between Bradbury and sort-of Lorenz—was suggestive," says Yan. "We were closing in on something. And yet, all along, there was a nagging sense that something was unsubstantiated, that

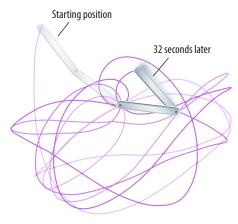
we were getting ahead of ourselves." Yan notes that a classical chaotic system, like a double-rod pendulum, still has an exact position and state of motion at any moment, while a quantum wave function generally has neither. "It was never entirely clear that wave functions were suitable quantities for exploring of quantum chaos."

Working this time with a colleague from Caltech, Yan set out to see if he could learn anything by trying to justify the use of wave functions in chaos studies. Borrowing a concept called "circuit complexity" from quantum computing, he analyzed the relative complexity of quantum wave functions in order to precisely quantify how much two initially similar wave functions will deviate from one another over time. This is the essence of chaotic behavior, slight variations in initial conditions leading to large, system-wide departures, and by this circuit-complexity measure—unlike the standard measures of wave-function overlap used in quantum mechanics that stay constant during the time evolution—the wave functions did indeed diverge with time. It even turned out that the complexity growth separating initially similar wave functions could be calculated with OTOCs.

The circuit-complexity approach clearly worked, and its connection to the OTOC was encouraging, but was it actually correct? To verify this, Yan performed a key consistency check in physics, examining whether his new approach would successfully reproduce known results in a situation that had already been solved. For example, Einstein's gravity theory, which properly governs extreme gravitational situations, such as a black hole or the big bang, reduces to Newton's much earlier gravity theory in less extreme situations, such as the orbit of the moon or the trajectory of a baseball. Yan was able to show that the circuit-complexity approach to *quantum* chaos properly reduces to the standard measure of *classical* chaos under appropriate conditions.

So here, at long last, was the Lorenz-type quantum butterfly effect. A quantum wing flap could theoretically produce a quantum tornado. And while a lesser scientist might have just declared victory, Yan felt there was something special about the way the OTOC, a Bradbury-type butterfly, naturally shows up in Lorenz-type quantum chaos. The interrelation implied fertile





If friction is neglected, a single-rod pendulum will forever trace out a consistent arc; if it is released from a different height, it will trace the same arc but climb to the new height with each swing. However, a double-rod pendulum follows a chaotic pattern of motion, swinging and swirling in a way that depends sensitively on the exact manner of its release. If the initial height is changed or the "elbow" is bent, even slightly, the resulting motion will be completely different. Here, a double-rod pendulum is released from two nearly identical initial configurations, and they rapidly diverge onto very different paths. This is an example of the Lorenz-type butterfly effect: small changes in initial conditions readily progress to large changes in outcome.

CREDIT: adapted from Ari Rubinsztejn/Wikipedia

ground for exploration—and perhaps a hidden reality yet to be revealed.

#### The anti-butterfly effect

Yan and his Los Alamos colleague Nikolai Sinitsyn set up an experiment to test the quantum butterfly effect, Bradbury-style, on an IBM-Q quantum processor.

A regular, nonquantum computer performs calculations by taking a bunch of bits of information, ones and zeros, and sending them through a complicated "logic circuit," the elements of which are called gates. Along the way, the ones and zeros interact with one another. (For example, the AND gate compares two bits and returns a value of 1 only if both bits were already 1; if either was 0 to begin with, the gate returns 0.) A quantum computer does its calculations the same way, except that it uses quantum bits, or qubits, and has some additional gates that only work with qubits.

## Entangled qubits might be exploited to provide a reliable rescue against information loss.

Qubits differ from classical bits in two important ways. First, they carry more complicated information than a binary one or zero. Second, when they interact with one another as they are passed along a logic circuit, they become "entangled," meaning that they cease to be purely individual qubits and instead share their states. Probing one member of an entangled group of qubits—for example, checking its value—will in some way affect the state of all the others.

Yan and Sinitsyn created a complicated logic circuit and prepared a group of qubits to send through it. However, for this experiment, they sent the qubits through the circuit in reverse order—the last gate first, the first gate last—to simulate the qubits' states evolving backward in time. Once the qubits had passed backward through the circuit, becoming entangled along the way, the scientists measured the state of one qubit. Because measurements in quantum physics affect the object being measured in an unpredictable way, this measurement amounts to deliberately damaging the state of that qubit and therefore the information it carries. In addition, all of the other qubits entangled with it would also be partially modified.

But here's the trick: now, Yan and Sinitsyn send the qubits, including the directly damaged one, forward in time—i.e., passing through the circuit of logic gates again, but this time in the proper forward direction. To their great surprise, the scientists found that the damaged qubit, once returned to the present, was actually in its original state (the "before time travel" state), modified only by some small background noise. The same was true of all the other qubits. As long as the circuit is complicated enough to produce significant entanglement among the qubits, the potential damage is curtailed; any information damaged in the past is recovered in the present.

"It's effectively the *opposite* of the Bradbury-type butterfly effect!" says Yan. "At the quantum scale, reality is self-healing. Entanglement is preserving the present, protecting it."

#### Better living without butterflies

Successfully exploring the nature of the quantum butterfly effect—via either perspective, Lorenz or Bradbury—would have been prize enough. But Yan and his colleagues got an extra bonus with the discovery that natural entanglement serves to restore damaged information. And this quantum anti-butterfly effect now that it is known to exist—can be put to use.

The most obvious application is a straightforward assessment of "how quantum" a quantum computation is. To what extent is a quantum computer actually making use of its quantum resources, rather than relying on its classical ones? "In principle, finding the answer is simple," says Yan. "Create a forward-and-backward logic circuit to check for the preservation of information. Since

> the anti-butterfly effect is a purely quantum phenomenon, the degree to which information is protected represents the degree to which it is quantum information to begin with."

> More ambitious, perhaps, would be a direct information-security application. In principle, any information can be encoded in qubits and protected from damage with a forward-andbackward logic-circuit operation. Whether the

threat of damage comes from a prosaic vulnerability—such as a power surge, a computer glitch, or ever-present natural radioactivity affecting physical circuitry—or from a deliberate cyber attack, the anti-butterfly nature of entangled qubits might be exploited to provide a reliable rescue.

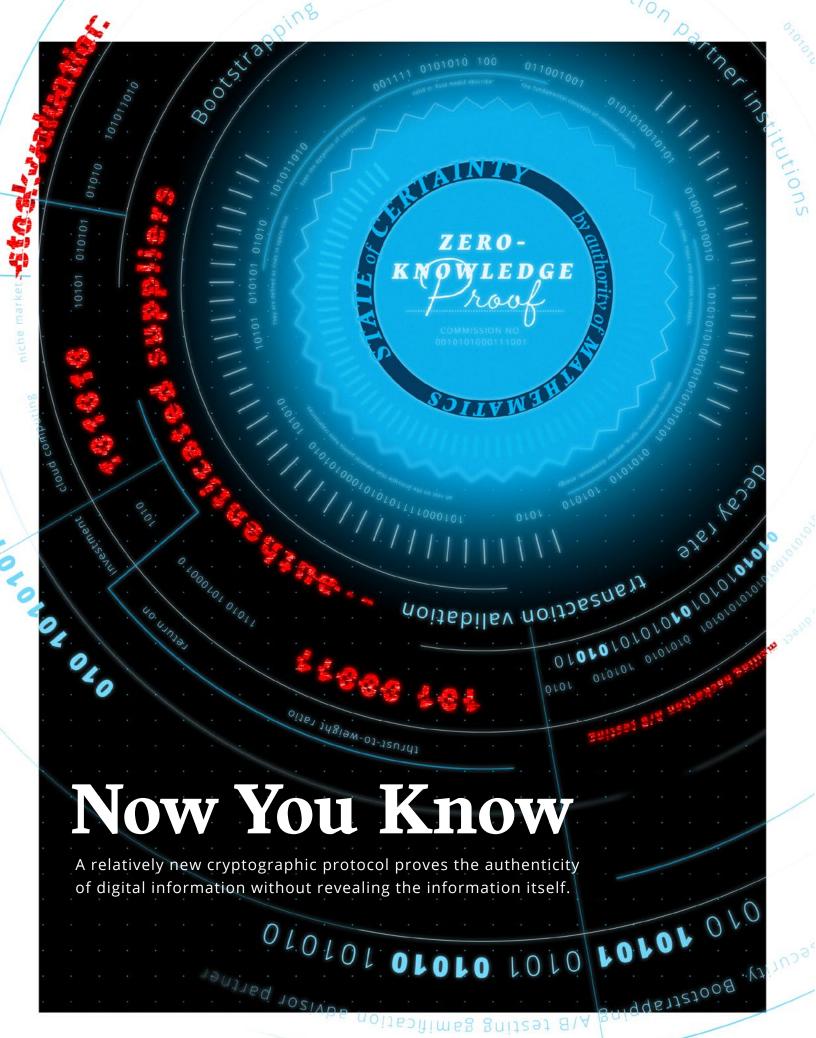
And of course, there's the most important application of all: when we finally do learn to send people back in time, maybe we can construct a suitable quantum anti-butterfly gizmo to prevent time-travel tourists from disturbing the timeline we've all come to know. LDRD

—Craig Tyler

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THE EASIEST WAY TO CHEAT on your math homework is to find the answers somewhere, such as the internet or an answer key. The best way for a teacher to prevent this kind of cheating is to issue the widely dreaded requirement to "show your work."

Showing the work usually reveals whether that work is legitimate and original, but it's a burden: the teacher must now review every student's every line of work. This may be a burden some teachers are willing to accept, but what if, instead of the answer to a math problem, one were trying to prove the veracity of satellite imagery (which could have been intercepted and faked)? Or the proper manufacture and assembly of parts for a nuclear weapon (which could have been subtly sabotaged)? Or the output from a computer network that controls critical infrastructure (which could have been hacked)? Or the accuracy of scientific experiments, data, and analysis (which could have been biased)?

In such cases, evidence of tampering, or some other manner of inauthenticity, may be expertly hidden in one small corner of the greater whole. And even if a "show your work" approach were sufficient in theory, finding one incongruous detail in the endless terabytes needed to prove the validity of such complex information would be a nearly hopeless task. Moreover, it would require actually *showing*—sharing, transmitting, publishing—"your work," thus putting sensitive information at even greater risk.

Is it possible to prove, even to yourself, that you know some piece of information without personally witnessing its entire detailed history? Is it possible to prove to someone else that you know some piece of information without ever revealing the information itself—or, indeed, without revealing anything at all, other than the fact that you know it?

#### Trust me—or better yet, don't

The solution to this rather esoteric challenge is something called a "zero-knowledge proof" (ZKP). It's a technique that cryptographically encodes a small, robust, random sample of what "showing your work" would entail—evidence of a spot check, of sorts, but without including any of the actual work—together with a clever mathematical manipulation designed to ensure that any data tampering, no matter how small or well hidden, is overwhelmingly likely to get picked up.

"The math of it has already been worked out," says Michael Dixon, a scientist in Los Alamos's Advanced Research in Cyber Systems group. "The biggest challenges today are scalability and integration for real-world application, which require *really* understanding precisely what you are trying to prove in the first place."

Dixon likes to boil it down to its fundamentals.

"Remember those 'Where's Waldo?' books?" Dixon asks.

"The ones that show intricate cartoon scenes with tons of characters, and you're supposed to find one particular character called Waldo? Well, suppose five kids are looking for Waldo, and it's a race—who will find him first? Who will find him second? But even if you manage to find him in that complicated illustrated jumble, you can't just say you found him; you have to prove it somehow. Yet how can you prove it to the other kids without giving away his location (say, by pointing) or any information that might help them find him (such as 'upper-left side of the page' or 'near the circus elephant')?"

There are multiple ways. One way, for example, is to create an answer key: write down Waldo's location and share it only after everyone has found him. This type of solution works if the information loses its sensitivity or importance after a short amount of time—once the game ends, in this case. There may be a limited set of real-world situations in which that sort of solution would suffice—proving some information was previously known by revealing it later—but it wouldn't be the majority of them.

Perhaps a better way would be to involve a third party, someone all the kids trust—a parent maybe—and then one-by-one whisper Waldo's location into the parent's ear. Each time, the parent affirms that a particular kid has found Waldo. But deep in the information age, when the task at hand is not a game and the data to be verified is more complicated

# Zero-knowledge proofs are TRUSTLESS YET TRUSTWORTHY.

or sensitive than the location of a cartoon character in a striped shirt and a beanie hat, finding a suitable "parent" to trust is not always a simple matter. It turns out that the legitimate authorities we rely on for this task now may not be entirely trustworthy, despite their best intentions. In recent years, hacking attacks have seen vast quantities of sensitive personal data stolen from large retail companies, a major credit agency, and even a key federal office dedicated to national security.

"We want to shift the nature of the task," says Dixon. "Instead of vetting particular organizations to verify their trustworthiness—federal agencies, banks, defense contractors, and so on—we assume everyone is equal. We don't want to have to trust anyone—or suspect anyone, for that matter." He explains that it's a little like using a notary, only without the notary. A software-based "stamp" of authenticity proves that the information is valid without revealing the information itself, just as a notary stamp proves a document was legally signed by the proper people without attaching their photo IDs.

The difference lies in not having to license and trust a human notary, who could be impersonated, bribed, or simply distracted. It's trustless yet trustworthy.

## It's not what you know, it's that you know

A proof could take the form of an entire "show your work" explanation. ("I started looking for Waldo in the upper-left corner and worked from left to right in one-inch-tall rows, pausing every time I saw a pattern of red and white; when the first row turned up nothing, I started on the second row...") It could also require an interactive interrogation

and examination of large amounts of data or back-and-forth interaction (either of which may be impossible if the information being discussed is classified, for example).

A better solution is based on an important result in computational complexity theory known as the PCP theorem ("probabilistically checkable proof"). The theorem essentially states that if you have a mathematical proof of a particular length, it is possible to reconfigure that proof into a longer one that can be verified, with great accuracy, using only a random sampling of a very small subset of that longer-form proof. That's the spot check. The resulting cryptographic proof is something called a zk-SNARK: a zero-knowledge succinct non-interactive argument of knowledge. Here, the terms "succinct" and "non-interactive" eliminate the cumbersome varieties of ZKP. Succinct, in absolute file size, is typically only a few hundred kilobytes, or about one-tenth the size of a typical QR code. Non-interactive means

# It's difficult to overstate the **PUBLIC GOOD** that will **ULTIMATELY COME FROM THIS TECHNOLOGY.**

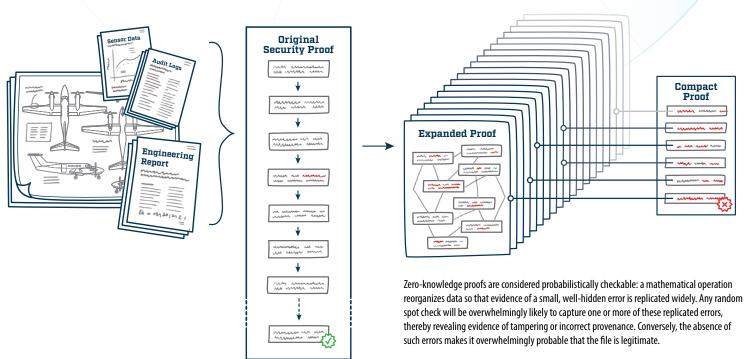
in which the party requiring proof poses a series of ancillary challenge questions intended to check if the prover really did the work ("What kind of animals did you notice in your search for Waldo? Were there characters wearing red-and-white stripes who were not Waldo? Were there any children in the lower half of the scene?"). But this extra information is undesirable. It requires the transmission

one-way communication: the zk-SNARK is provided, and that's that; no interrogation is necessary.

"In practice, the zk-SNARK is a form of encrypted data that hides where the proof was spot-checked," Dixon says. "If an adversary intercepted it and managed to break

the encryption, then he or she could create fake proofs—not ideal, obviously—but nothing more is at stake. It really is zero-knowledge and contains no sensitive content. It simply proves that the sensitive content—whatever it is and wherever it resides—is legit."

With zk-SNARKs, a complicated data product can be passed along between numerous parties—even explicitly distrusted parties—before it reaches its final recipient, and yet that recipient can be assured of the data's veracity in the end. Dixon refers to this as a "chain of provenance": at each stage of working with



a data product, a new zk-SNARK combines the verification associated with the current stage with the previous zk-SNARK, which verified all prior stages, confirming that the information was processed properly by all the appropriate computational procedures and not touched by anything else.

For example, one possible application of this technology is to verify remotely that a uranium enrichment facility is producing uranium suitable for power production. To do this, sensors at the facility might collect data that carries a cryptographic signature from the sensor itself. The signed sensor data could then be combined with enrichment claims made by the facility and fed into an algorithm that combines results from different sensors in order to confirm that they correspond to the specified enrichment level. That algorithm could output a zk-SNARK to be presented to international regulators. At every point, a single zk-SNARK is generated and passed forward, confirming everything that happened prior: the sensor data is valid, the correct algorithm analyzed that exact data, and no one tampered with the results. The final zk-SNARK doesn't contain any sensitive information no actual sensor data, no algorithms, not even the enrichment levels themselves, necessarily; rather, it simply attests that the policy-compliant enrichment-level claims made by the facility operator are confirmed (or not).

#### Private information, public security

From a national security perspective, ZKPs have immediate value. The U.S. military, for example, needs to verify that the complex defense systems it purchases from large numbers of private-sector contractors and subcontractors have been built precisely according to approved specifications. They must have properly sourced parts and be correctly assembled, carefully transported, and faithfully deployed—all succinctly and convincingly verified at every step of the way without having to take the whole thing apart or, in the case of nuclear weapons, perform a weapons test, which is inhibited by international treaty. (Similarly, complex civilian products involving foreign or domestic private-sector subcontractors can be reliably tracked and verified by sharing only zk-SNARKs and thereby not sharing any proprietary information.)

The military needs to convince not only itself, but also its adversaries, that it has robust and reliable defense capabilities. There may be times, for example, when the United States may wish to outwardly demonstrate and prove that it has the ability to defend itself against a particular class of cyber weapon, such as one designed to disrupt electrical power or other infrastructure systems. In such a case, it is important to trustlessly prove that the defensive capability is real—without revealing how it works or how it can be circumvented.

In addition, numerous important applications today, whether for defense or private industry, require machine learning: computers or vast networks of computers that learn how to do a task via experience and goal-seeking, just as human beings learn tasks. Want to teach a computer how to drive a car? Show it thousands of photos containing intersections, street signs, other vehicles, and pedestrians; show it thousands of videos of merging and parking, what to do and what not to do. Then let it attempt to replicate good driving in a simulation until it masters the task.



# Blockchain without the blockchain

In the civilian regime, perhaps the best-known example of a verification system without a central trusted authority is cryptocurrency, such as Bitcoin. Cryptocurrencies are designed to be exceptionally secure against the vulnerabilities of trust-based systems: bank errors or insolvency, identity theft, inflation from "printing money," or having assets frozen because of austerity measures or suspicion of a crime. Such security, however, comes at a price.

Different cryptocurrencies use different protocols, but they usually involve a blockchain: a list of every transaction ever processed since the cryptocurrency was invented. Maintaining the blockchain across a trustless network of computers has its challenges. In some cases, a copy of the entire blockchain is located, unencrypted, on every computer in the network—a clear strike against the privacy of transactions. And adding new transactions to the existing blockchain might require each computer in the network to grind away on some deliberately difficult math problem in order to prove the validity of its work, with new transactions affirmed only when the overall network of computers achieves a consensus answer. This represents a tremendous increase in system-wide information-processing requirements relative to a traditional trust-based system. Without ZKPs, blockchains have a steep tradeoff between verifiability and privacy.

In principle, however, a system using zk-SNARKs—and several are in various stages of development—eliminates these kinds of difficulties. The system is still trustless, but to become so, it does not sacrifice privacy, amplify information processing, or require consensus across a global network. Instead, each new transaction or piece of information is convolved with the previous zk-SNARK to create a new zk-SNARK, and that file, about one-tenth the size of a typical selfie, affirms that everything is on the up and up.

Want to teach a computer to recognize faces? Show it millions of faces from every possible angle and in all sorts of lighting. Then allow the algorithm to self-adjust with a set of parameters that leads to correct identifications.

Dixon and his student, Zachary DeStefano, who is entering a doctoral program in computer security, set out to secure output from machine-learning results—or just to make sure you got what you paid for—you need a succinct, non-interactive way to prove that the correct neural network, set up exactly as you specified, processed the inputs you provided and no others."

Last year, Dixon and DeStefano wrote a software program to do exactly that. It produces a zk-SNARK to validate both the inputs and the specific network execution for a system trained to recognize handwritten numbers. Without supplying a massively cumbersome log of all the scribbles in the dataset, of every single value of every variable the neural network adjusted, of what

# Any data tampering, no matter how small or well hidden, is **OVERWHELMINGLY LIKELY TO SHOW UP.**

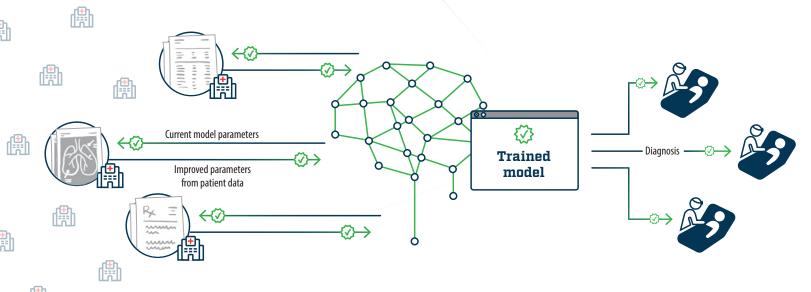
systems called neural networks. Neural networks are complex algorithms that use many nodes, each with parameters that must be learned through experience, to simulate processing by neurons. Dixon and DeStefano's solution, unsurprisingly, involves ZKPs.

"The most powerful neural-network models are based on datasets much larger than what any one organization can house or efficiently collect," says DeStefano. "We live in an era of cloud computing, and neural-network computations are often subcontracted out. To validate critical

outputs the countless iterations produced, or of how the network learned to improve its accuracy, the proper processing was nonetheless successfully confirmed.

But with neural networks, there's another concern: their training. A ZKP is needed to account for the authenticity of the training set originally supplied to the neural network, which, often, the customer has no part in. Dixon and DeStefano are working on that now.

For example, imagine if, at the outset of the COVID-19 pandemic, a neural network were set up to analyze medical data from millions of patients from all over the country to determine if their lab tests and scans indicated COVID-19 and to assess which treatments proved most effective on which patients. The trouble is, medical data are confidential. How could the neural network



An example of zero-knowledge proofs (ZKPs) in action: Suppose that, early in the pandemic, a neural network were set up and trained on every useful bit of information from every COVID patient in the country (or the world). Before there were even COVID tests, there could be diagnoses based on patient bios, symptoms, blood tests, and medical scans—plus suggested courses of treatment based on what worked best for similar patients. Neural networks operate by creating a vast network of interlinked nodes that approximate the behavior of neurons in the brain, each with one or more adjustable parameters. Through an iterative process involving training data, the parameters are dialed in to their optimal values. Thus, patient data from various sources (left) are processed by a neural network (center) to create a model that doctors can use to diagnose and treat other patients (right).

However, patient data are private. Los Alamos cyber security researcher Michael Dixon proposes adding ZKP capabilities to a previously published distributed-computing architecture to allow patient data to remain firmly with the doctors, hospitals, or testing centers that generated them. Instead of sending the data to the neural network, the network repeatedly queries every distributed source: "Here's the current state of the model; based on your new patient data, how should we adjust the model parameters to make it better?" The response is easily calculated at each source location and does not specifically include any actual patient data—only a ZKP proving that the data were properly used to generate the answer. This methodology could be used in many similar situations to prevent an undesirable transmission of data—whether the concern involves privacy, national security, or even just an overwhelming quantity of data.

be trained with huge quantities of valid patient data if the data can't be shared outside of the hospitals, labs, imaging centers, and doctors' offices where they were obtained? Encryption is a limited approach, since the data still move over the wire; a better approach involves transmitting only the ZKP-verified information necessary to train the neural network and not—true to zero-knowledge principles—the actual patient data.

"We're working to help a distributed system for crowdsourced training data audit itself," Dixon says. "The idea is to delegate neural-network training to the edge nodes, such as hospitals, and require them to furnish proofs that they did their jobs correctly." The neural network still seeks to improve its parameters through iteration, but instead of asking edge nodes for patient data explicitly, it only asks in what direction and by how much to shift the current-iteration parameters to achieve an improvement. Earlier research proved that the edge nodes can perform that computation, and Dixon and DeStefano are now demonstrating that zk-SNARKs can verify that the edge nodes did (or didn't do) exactly what they were supposed to. The result is a perfectly reliable neural network computation and a hugely valuable medical resource constructed from enormous quantities of verified patient data that were never actually shared. And by virtue of the zk-SNARKs, the system automatically recognizes and eliminates training information derived from faulty patient data, whether the error comes from a mistake or deliberate sabotage.

"With many commercial technologies, there's this classic tradeoff between security and privacy," says Dixon. "But with ZKP technology, it's no longer either-or. We can have the best of both worlds."

Eventually, Dixon hopes to see specific hardware designed to produce inherently self-verified data for neural-network training and general computation. It will ultimately be possible to use quantum effects to verify electronic recordings of all kinds (such as from x-rays or blood tests, in the COVID-diagnostic example). The data would be quantum mechanically guaranteed and cryptographically certified upon creation, with subsequent zk-SNARKs generated as needed to verify the proper processing and the absence of tampering.

#### Better informed with zero knowledge

"Where we are now—verifying inputs and execution, securing data sources and supply chains—is just the beginning," says Dixon. "In a world concerned with massive-scale misinformation, it's difficult to overstate the public good that will ultimately come from this technology."

For example, Dixon sees many opportunities to improve the election security infrastructure that supports the American democracy. Since 2016, the threat of external interference in American elections has been thrust into the national consciousness. And a major channel for such activity, potentially misleading information shared on social media, while problematic already, is about to get much harder to control with the proliferation of deliberately deceptive but visually convincing videos known as deepfakes. These might show prominent politicians saying embarrassing things they never actually said, yet in terms of video quality, they are virtually impossible to distinguish from actual recordings.

But at its heart, the deepfakes problem is really a chain-of-provenance problem, which is exactly what ZKP technology addresses. A video file's history needs to be verified—when, where, and by whom was the video recorded? What level of video editing has taken place since—color adjustments only, or splicing in additional footage? It's unreasonable to track all this information in detail for every video on the internet, but rather than "showing your work," a zk-SNARK would be sufficient to verify that the video's veracity has been confirmed. Web browsers, perhaps, could implement a content filter based on valid ZKP stamps (or at least display a warning message when the stamps are missing or invalid). And if all of that sounds overly technical, not to worry: Dixon is always ready and willing to break it down.

"Our democracy is vulnerable to disinformation shared online," he says. "But hopefully soon, a straightforward mathematical operation, carried in a tiny computer file, will counter that vulnerability."

Digital information, national security, financial transactions, critical supply chains, facial recognition, scientific data, infrastructure controls, and democracy itself: across the board, zero-knowledge proofs can make us stronger.

Now you know. LDRD

—Craig Tyler

# MORE CYBER SECURITY AND SYSTEMS AT LOS ALAMOS

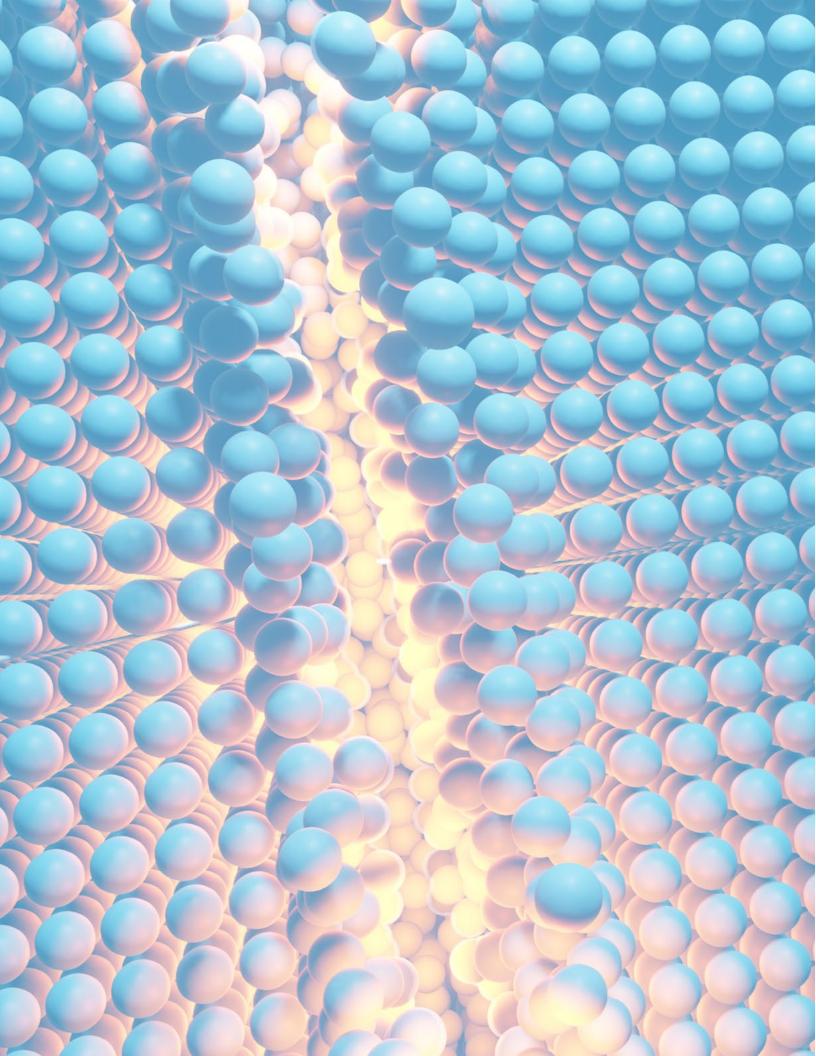
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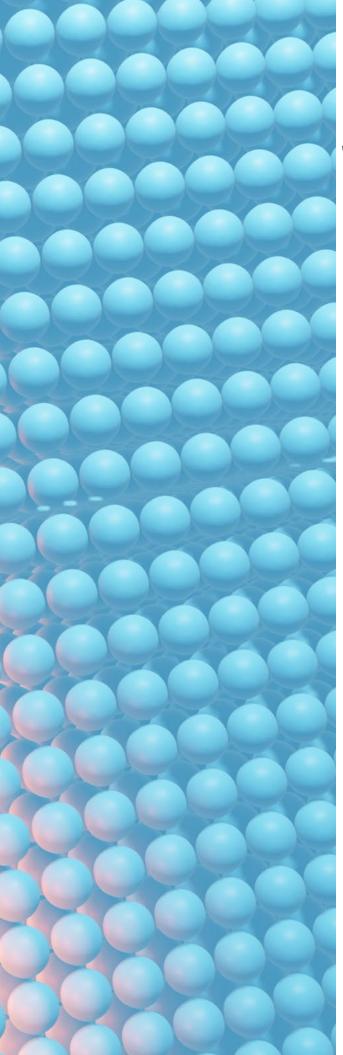
- Neural networks
  - "The Mind in the Machine" | January 2020
- Securing the power grid

"Out of the Dark" | February 2019

- Analyzing malware "Catching Code" | May 2017
- Quantum cryptography
- "Safety in Numbers" | May 2015
- "Secure Communication Now and Forever" | March 2011
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  - "Intruder Alert for the Cyber World" | November 2013

from 1663





# WHEN ATOMS GET OUT OF LINE

HOW MATERIALS ARE IMPACTED BY THE EXTREME CONDITIONS OF A NUCLEAR REACTOR

THE INSIDE OF A NUCLEAR REACTOR is a treacherous place. Neutrons, escaping from unstable, radioactive atoms, collide with neighboring atoms, causing their nuclei to burst apart, which releases more neutrons that pummel additional neighbors in a cascade of fission reactions. The whole process is carefully controlled using multiple strategies, including strong containment vessels, to ensure safety. These containers, however, are not completely spared from the ricocheting atoms and rogue neutrons, and over time they accumulate damage and can no longer be used.

Scientists at Los Alamos National Laboratory are leading a multi-lab effort to study the steel used to make these containers. Instead of simply surveying the damaged steel from an old reactor, they are trying to understand the fundamental science about what is happening to the atoms that comprise the steel.

"The reactors of the future could be even safer and more economical if they use materials that are optimized for harsh conditions," says Blas Uberuaga, Los Alamos physicist and director of the multi-lab effort called FUTURE (Fundamental Understanding of Transport Under Reactor Extremes). "We want to gain a mechanistic understanding of how radiation, corrosion, and heat impact materials, and our expectation is that this understanding will translate into real systems down the road."

#### A nuclear future?

Currently, 440 nuclear reactors distributed among dozens of countries produce about ten percent of the world's electricity. Although nuclear energy is a reliable source of electricity that does not rely on burning fossil fuels or release significant carbon emissions, the extent to which nuclear energy will be included in the future energy needs of the United States is currently in flux. Most existing reactors were built in the 1970s and 1980s,

and many have reached or are nearing the limit of their intended operational lifetimes. Furthermore, concerns about safety and the buildup of radioactive waste have kept the production of new reactors at bay for decades.

Today, with accelerated concerns about increasing energy needs and climate change, proponents of nuclear power are convinced that new reactors should be a vital part of the energy portfolio. To this end, many private companies are charging forward with new reactor strategies and designs. In addition, multiple Department of Energy programs are dedicated to modeling and testing alternative fuels, coolants, and next-generation reactors, as well as researching the fundamentals of nuclear power to enable innovation.

With next-generation reactors, many things are possible. For instance, new types of fuel or reprocessing

# NUCLEAR ENERGY DOES NOT RELY ON BURNING FOSSIL FUELS OR RELEASE SIGNIFICANT CARBON EMISSIONS

help increase efficiency

and possibly repurpose radioactive waste, and coolants other than water could make reactors safer by reducing the chances of a meltdown. However, the materials that make reactors will still be subjected to extreme environments that will limit the lifetimes of their safe usage. Critically, in many cases, reactor materials are simultaneously exposed to more than one such extreme environment, such as irradiation and corrosion. FUTURE is specifically targeting the coupling between these multiple extreme environments.

"There will always be corrosion, but it's a question of how much and how fast," says Peter Hosemann, professor at the University of California at Berkeley and deputy director of FUTURE. FUTURE is a Department of Energy-funded Energy Frontiers Research Center that combines expertise at six U.S. institutions: Los Alamos National Laboratory, The University of California at Berkeley, Pacific Northwest National Laboratory, North Carolina State University, Bowling

Green State University, and the University of Virginia. Through a combination of modeling and experimentation, scientists in the FUTURE project are working together to pinpoint exactly how irradiation impacts corrosion in different types of materials and corrosive environments. With this information, they can help the nuclear power community make more informed choices about the best materials to use in next-generation reactors.

#### Solids aren't so solid after all

Uranium-235 is the fuel that powers most of today's nuclear power reactors. For the reactor to work, small pellets of uranium modestly enriched with this isotope are encased in metal rods that are bound together in a steel assembly, surrounded by a coolant such as water, and contained in additional steel vessels. The energy released from the fission reactions within the fuel rods heats the water and, through a number of heat exchanges, steam eventually drives a turbine generator to create electricity. The fission reactions are controlled, but ultimately the metal fuel rods and steel containment vessels deteriorate from radiation exposure and corrosion damage and are no longer safe to use.

Steel is a common structural material used in many parts of nuclear reactors. It is an alloy of iron and carbon but often includes chromium, nickel, or other elements—together they make steel a strong and versatile material. However, this solid compound that is commonplace as the skeleton of skyscrapers and bridges is not as inert as it looks; when in proximity to nuclear fission reactions and coolants, the lattice of steel atoms can be both physically and chemically disrupted.

The physical disruption happens when an incoming neutron from a nuclear fission reaction strikes the steel, forcing a few atoms out of order through elastic collisions. This irradiation can result in an empty space, or vacancy, in one part of the lattice, and a build-up of displaced atoms, called interstitials, in another part of the lattice. Furthermore, this disruption makes nearby atoms shift and shuffle, causing the vacancies and interstitials to essentially migrate until they reach a trap, such as a grain boundary. (Grain boundaries are places where small crystals of the material meet and don't match up perfectly.)

During this shifting and movement many things can happen: the vacancies can combine with other vacancies to become larger voids, or the vacancies can heal if they encounter out-of-place interstitial atoms, thus shrinking the voids and re-joining the lattice structure. Interstitials can also aggregate, forming large disk-like clusters of extra atoms called dislocation loops within the materials. Moreover, neutrons can also induce nuclear reactions within the steel that can create new elements that were not originally in the lattice—including gases that make bubbles in the metal or unstable atoms that can even initiate further radioactive decay. All of these defects can ultimately lead to macroscopic changes in the properties of the material and, in many cases, cause a loss in performance such that the reactor may not optimally operate as long as expected.

Chemical deterioration, or corrosion, is also a significant concern, and understanding how corrosion happens to different materials is vital. Rust is a familiar type of corrosion that appears when iron atoms combine with oxygen to form layers of iron oxide on the outermost part of a metal. As rust layers thicken

and spread, the material structure is compromised. However, some oxide layers are helpful; many types of steels are considered "stainless" when they include a thin, protective chromium oxide or other oxide layer on their surface.

Various types of stainless steel are used in reactors, and most currently operating reactors use water as a coolant. When fuel assemblies are submerged in water, any defects in the metal lattice provide opportunities for the metal atoms to interact with water's oxygen and hydrogen atoms, thus accelerating the possibility of

corrosion. In this oxidizing environment, the thin oxide layers can protect the metal as long as they are the optimum thickness. Other coolants that can be used instead of water include liquid metals, molten salts, or even gases, but these coolants can introduce other types of corrosion.

"We know that corrosion can occur when there are defects in the material, and we know radiation increases defects," explains Uberuaga. "However, we want a deeper understanding of when irradiation will influence corrosion and how."

To gain this understanding from such a complex environment, the FUTURE scientists are tackling the challenge from many angles and breaking it down into easier-to-interrogate pieces. For instance, instead of using steel for experiments, they

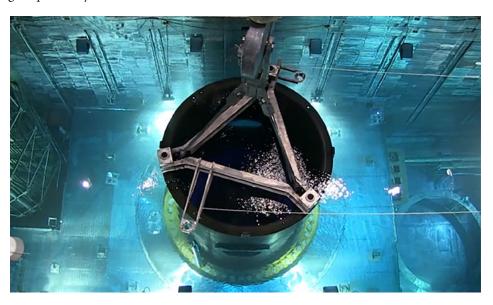
are examining simpler, surrogate materials like iron-chromium binary alloys. They are conducting separate experiments to study void generation and oxide formation, while other studies are combining these different effects in one experiment. Finally, the scientists are using advanced multi-scale models to predict and validate their results.

#### Watching atoms one at a time

Although the FUTURE project research is spread out among all the partner laboratories, a number of experiments are taking advantage of the Ion Beam Materials Lab (IBML) at Los Alamos, which is one of very few accelerator facilities dedicated solely to materials research. Here, particle accelerators can simulate the conditions of a reactor by using high-energy protons or heavy ions to induce radiation damage. This is better than using neutrons because it's easier to control, less expensive, and doesn't cause the material to become excessively radioactive. Once a sample is damaged, various techniques can be employed to examine the results.

In recent work, FUTURE scientists used ion beams at the IBML to irradiate samples of iron-chromium and then examined the defects using transmission electron microscopy (TEM). They also took some of the irradiated samples to the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) research center in Germany to study the defects using an advanced, complementary technique called positron annihilation spectroscopy (PAS). Together PAS and TEM data could give the scientists a more complete understanding of the damage, and right now, HZDR is one of only a few places worldwide with this kind of positron capability.

Positrons are anti-electrons: electrons and positrons have the same mass but electrons are negatively charged and positrons are positively charged. When a positron meets an electron, they annihilate one another and release energy called annihilation radiation, which can be detected via spectroscopy. This is a useful tool for looking at vacancies and voids in an irradiated sample because positrons trapped in the voids take longer to annihilate, making it possible to deduce how much of the material is consumed with voids.

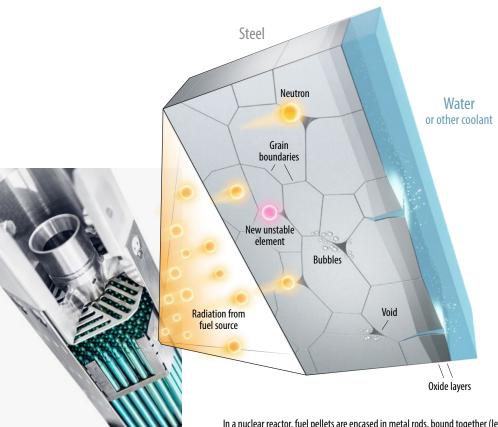


A reactor vessel submerged in water at a nuclear power plant. Most nuclear reactors currently in operation use water to cool and moderate the nuclear fission.

The TEM and PAS analyses of the Los Alamos samples revealed details about how vacancies accumulated into clusters, but it also revealed how preexisting voids from the material's synthesis had shrunk in size as a result of irradiation. Together, these data reinforce the idea that the damage is dynamic and can change over time—but this change can happen quickly after radiation is lifted; in some cases the damage state relaxes within a few seconds or minutes. For this reason, the FUTURE team—with help from Los Alamos science investment funds—is developing a new, unique positron capability at the Lab to measure the damage as it happens.

Bowling Green State University Professor Farida Selim leads the point defects thrust area of FUTURE. Selim arrived in Los Alamos in January 2021 to work with Yongqiang Wang, Director of the IBML, to set up a positron beam between two of the existing accelerators. The plan is to use an ion beam to introduce displacement damage in a sample (simulating radiation), a second beam to implant helium (simulating gas formation), and finally the positron beam to simultaneously allow extremely sensitive detection of the damage as it is created.

To enable PAS, the positrons emitted by a radioactive sodium-22 source are first slowed down and their energy is equalized, then they are transported through a magnetic field and bunched into very short pulsed beams (roughly a 100-picosecond (ps) pulse duration—100 trillionths of a second). By measuring how long the positrons live before they are annihilated, the scientists can infer the size of the individual



In a nuclear reactor, fuel pellets are encased in metal rods, bound together (left), and immersed in a coolant such as water, liquid metal, or molten salt. The whole assembly is then encased in steel structures. Radiation from the fuel and corrosion caused by the coolant can together damage the metal. For instance, radiation can disrupt the atoms in the steel, resulting in empty spaces, or voids, which in turn can grow or shrink and sometimes migrate to grain boundaries where the steel crystals don't line up perfectly. Furthermore, the radiation can induce nuclear reactions to create new elements—including gases that make bubbles or new, unstable atoms. Finally, oxide layers that normally protect the steel might grow thicker and flake away—exposing fresh material to corrosion—when water attacks the metal.

vacancies and vacancy clusters. Each positron lives only about 100 ps, but they survive longer—up to a few hundred picoseconds—when encountering vacancies or voids,

# WE WANT A MECHANISTIC UNDERSTANDING OF HOW RADIATION, CORROSION, OF HOW RADIATION, MATERIALS AND HEAT IMPACT MATERIALS where there

are fewer electrons with which to annihilate. The positron beams can also be accelerated at different energies, allowing annihilations to occur at different depths so that damage variation as a function of depth can be mapped out.

"The positron technique could allow us to see just one missing atom," explains Selim. "This is compared to electron microscopy which can only measure large defects, the size of at least several hundred if not thousands of atoms." When finished, the capability in Los Alamos will be the first of its kind in the world, offering a unique way to characterize the propagation of physical damage in multiple materials in situ.

#### Mimicking the hot zone

In 2004, Berkeley professor Hosemann was a student at Los Alamos. He recalls the time, during a workshop in Italy, that he began to think about studying irradiation and corrosion together.

"I realized that if you want to incorporate radiation damage into corrosion analysis, you must study synergistic effects," says Hosemann. This is because in a nuclear reactor, the two phenomena are inextricably linked.

Hosemann set out to create a proof-of-concept irradiation and corrosion experiment at the IBML in which he could study both phenomena at once. The experiment, which he called ICE, for Irradiation and Corrosion Experiment, would mimic the

conditions inside a nuclear reactor by irradiating a sample piece of metal—this time using a proton beam—while simultaneously

exposing that sample to a corrosive environment. The results were promising, prompting a second attempt in 2012, and the third iteration of this approach (ICE-III) is now part of the FUTURE project.

The ICE-III experiment requires a device that holds two sample foils of metal—each about 50 micrometers (millionths of a meter) thick—one on either side of a corrosion chamber. A proton beam delivers radiation, and various agents can be added to the corrosion chamber to mimic the types of coolants. University of California at

Berkeley graduate student Franziska Schmidt, who works with Hosemann and Wang, came to Los Alamos in 2019 to redesign the ICE-III chamber and integrate it with the proton beam in the IBML.

"We want to understand the formation of the oxide layer," says Schmidt. "Does the radiation make the oxide layer grow quickly, or does it form more slowly?" Because an oxide layer that quickly grows too thick and spalls off cannot protect the metal, Schmidt explains that the ideal situation would be to have an "oxide layer that has a growth rate slow enough that it is maintained for the life of a reactor." Conversely, if radiation were to cause

the runaway growth of an otherwise stable oxide, it could cause drastic deterioration of the steel in the reactor.

A preliminary study from last year demonstrated that over time or increased temperature (which is yet one more factor that can influence damage in materials), the oxide layer on a foil sample grew thicker, but the density of voids actually decreased. This experiment demonstrated the importance of time and temperature on oxide growth, but the effects of radiation are still largely unknown, which is why the ICE-III experiments will be critical.

One advantage of the ICE chamber approach is that the scientists will be able to easily test multiple metal foils with various corrosive agents such as water, liquid metal, or molten salts. Liquid metal and molten salts are two alternative coolants that could be safer and more efficient if used instead of water to surround the reactor fuel. The ICE chamber also enables the scientists to control radiation damage rates and temperature to increase their overall understanding of the effects of extreme conditions.

So far, Schmidt and the FUTURE team have been focused on studying the corrosive activity of a lead-bismuth mixture, which is one kind of liquid metal coolant. As of this printing, results from the first experiments using the ICE-III chamber with simultaneous liquid-metal corrosion and proton irradiation are currently being evaluated. The chamber is also being adapted to allow for similar studies using molten salts as the corrosive agent.



A thin sample of metal about 50 micrometers (millionths of a meter) thick is added to the unique corrosion chamber used by the FUTURE team. The chamber allows scientists to irradiate the sample while simultaneously exposing it to a corrosive agent in order to study the synergistic effects of irradiation and corrosion.

By testing multiple films in various coolants, the scientists hope to ultimately characterize how, fundamentally, irradiation impacts corrosion for each material, depending on the type of reactor coolant. For instance, some studies have shown that in a molten salt environment, the presence of radiation actually decreases corrosion under certain circumstances, contrary to the situation with water and liquid metals. However, the mechanism is confusing and still unclear, further emphasizing the overall complexity of irradiation and corrosion. Overall, by elucidating these types of specific and unique interactions, more robust materials can be developed and coupled with the appropriate coolants.

#### **Built to last**

The inside of a nuclear reactor is a treacherous place—but it doesn't have to be a mystery. Advanced, multi-scale modeling paired with realistic experiments can give scientists all the pieces they need to understand how various metal alloys are impacted by being in a nuclear reactor. However, since the behavior of the materials is vastly complex, scientists must be patient and diligently inspect all aspects to gain a thorough understanding.

"It's sort of like the parable about blind men feeling an elephant, trying to understand what it is by only examining one part at a time,"

# FUTURE REACTORS COULD BE SAFER FUTURE REACTORS COULD BE SAFER AND MORE ECONOMICAL WITH MATERIALS OPTIMIZED FOR HARSH CONDITIONS "We need to put all these

pieces together to get a big picture of what

irradiation and corrosion do, especially when a material is subjected to both at the same time."

By generating and validating data from these assorted experiments, the FUTURE scientists hope to not only understand the behavior that current material-coolant environments exhibit, but also predict how new, more robust materials options might respond. And if this big picture can come into focus, then the possibilities for the future of materials associated with nuclear power might become clear as well.

-Rebecca McDonald

# MORE NUCLEAR ENERGY AND MATERIALS AT LOS ALAMOS

http://www.lanl.gov/discover/publications/1663/archive.php

- Molten salt reactors "Refueling the Reactor" | January 2020
- Alternative fuel rod cladding materials "Safer Nuclear Power" | March 2013
- Making a miniature reactor "Power to the Planet" | August 2018
- The interface between material layers "Misfits in the middle" | May 2015

from 1663



# WAS THERE, IS THERE, ANYBODY THERE?

A SMALL NEW IMAGER MIGHT BE
THE TOOL TO FIND CONCLUSIVE
SIGNS OF LIFE BEYOND EARTH.

"A LOT OF PEOPLE ARE IMAGINING THE POSSIBILITIES OF CAVES ON MARS RIGHT NOW," says Los Alamos geologist Patrick Gasda. "When NASA decides to explore those caves, we want to be there."

Martian caves are exciting because they are among the most likely places to find evidence of ancient life. Planetary scientist Roger Wiens leads the Los Alamos OrganiCam project with Gasda, and elaborates, "A cave would be the place to look because Mars's surface has a lot of radiation and is very inhospitable. Caves are protected. The Current thinking is that any signs of life on Mars are going to be indicative of what was, not what is. Mars's climate has changed and is now far less hospitable than it once was. Scientists aren't ruling out the possibility of finding something contemporary, but they are focusing their search on signs of life that is long gone.

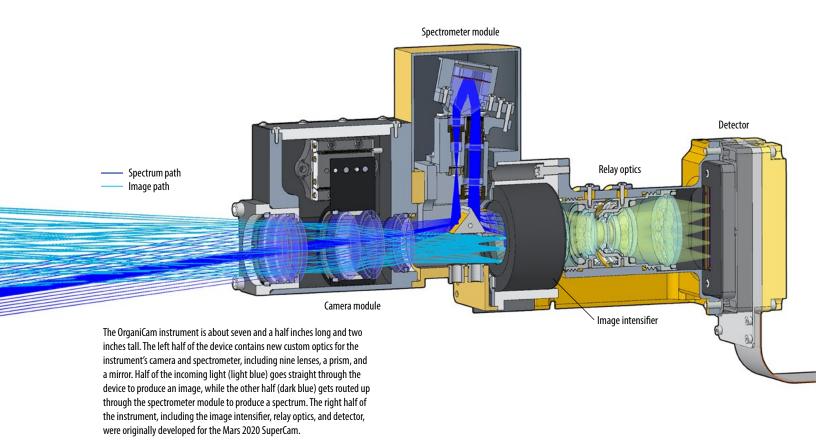
Wiens and his Los Alamos collaborators previously built SuperCam, an advanced instrument that arrived on Mars earlier this year aboard the rover *Perseverance*. SuperCam is a spectrometer-camera combo that uses a laser to analyze the chemical and mineral makeup of Mars's surface. Also onboard *Perseverance* is a miniature helicopter called *Ingenuity* whose mission is to prove it can fly in the thin, cold Martian air.

"We try to stay ahead of where space exploration is going," says OrganiCam engineer Benigno Sandoval, "so that we have the capabilities demonstrated by the time they are asked for."

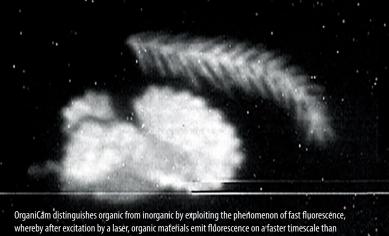
# A CAVE WOULD BE THE PLACE TO LOOK FOR SIGNS OF LIFE BECAUSE MARS'S SURFACE IS VERY INHOSPITABLE.

rover Curiosity discovered complex organic molecules, but they had been altered by the harsh environment, so it's hard to draw conclusions on whether or not their origins are biological. For something conclusive we need to look underground, and lava-tube caves offer the easiest access."

The team predicts that a flying organic-molecule detector, sort of a combination of *Ingenuity* with a mini-SuperCam, is going to be desired for the next Mars mission. The instrument has to fly, rather than drive, because the entrances to Martian subsurface lava-tube caves involve very long vertical drops. The idea is to send the instrument in, have it scan around inside the cave without landing, then return to the surface and transmit its data back to Earth.







OrganiCam distinguishes organic from inorganic by exploiting the phenomenon of fast fluorescence, whereby after excitation by a laser, organic materials emit fluorescence on a faster timescale than inorganic materials do. (Left) A photograph of strawberry leaves and a pine bough, both organic, together with various metals and a piece of petrified wood, all inorganic. (Right) Only the organic items' fluorescence is captured, highlighting possible bio-material against the complex background.

Developed at Los Alamos in collaboration with the University of Hawaii, OrganiCam has SuperCam heritage but is specialized to use images to discern organic materials from minerals—a key distinction in the search for life as we know it. While organic materials are not the same as little green men, or even little green microbes, they are an important first step.

"Don't get me wrong," clarifies Gasda, "finding microbes, or even fossils of microbes on Mars would be ideal!" But, in anticipation of the less-than-ideal, OrganiCam designers have set its sights on organic molecules specifically, because these are potential signatures of life.

The way it makes the distinction is by exploiting the phenomenon of fast fluorescence. Both organic and mineralogic materials emit fluorescence after being excited by a laser, but organics do so on a faster timescale than minerals. OrganiCam pulses a laser at its target, then opens its camera shutter for just 100 nanoseconds, capturing the fluorescence of the organics while excluding that of the minerals, which takes at least ten times longer to arrive.

to be intensified to be detected. Our image intensifier works like night-vision goggles, amplifying the signal by over 50,000 times."

Optics expert Adriana Reyes-Newell put together the optical assembly—laser aligning the mirrors and lenses for optimal performance. She explains, "Both functionalities use the same hardware, but they can't be done simultaneously. First you take the image, then you identify a spectroscopy target in the image, re-aim, remove the light diffuser from the laser beam path, then take the spectrum of the target."

The timing between the laser and the camera is tunable too, so photo series can be captured and stitched together into a sort of short movie. This captures the rate of fluorescence fade and provides additional information about the organic material under study.

Laboratory radiobiologist Kumkum Ganguly cast a wide net in terms of the kinds of organic materials that OrganiCam can detect. She has tested representative bacteria—from modern Earth bacteria (*E. coli*) to ancient Earth bacteria (cyanobacteria) and radiation-resistant *Deinococcus radiodurans*, nicknamed Conan

the Bacterium. To mimic an extraterrestrial environment and the kind of damage space radiation does to

# ORGANICAM CAN SCAN A ROOM AND IDENTIFY BIOLOGICAL CONTAMINATION INSTANTLY.

"What's cool about OrganiCam," enthuses Sandoval, "is that it has both a camera and a spectrometer. Most instruments do just one or the other, but OrganiCam can do both."

The signal entering the instrument gets split in two, with half going straight through the camera optics and the other half being diverted up through a different set of optics that make up the spectrometer. Both signals then go through the same image intensifier, detector, and processor (that's the part that came from SuperCam).

For spectroscopy, the outgoing laser light is collimated and concentrated on just one small target. But with the insertion of a diffusing filter, the light is spread over a larger area, more suitable for imaging.

"The laser pulse only lasts 5 nanoseconds," says physicist Ray Newell, "so the signals are very dim and short-lived; they need biomolecules, Ganguly irradiates samples with either gamma rays or high-energy neutrons for up to 48 hours—at which point any life is good and dead—before showing it to OrganiCam. The instrument not only clearly detects all bacteria tested so far, but it also picks up bacterial DNA extracts, which, depending on the harshness of the extraterrestrial environment, may be all there is to detect.

"Because we will train our instrument on a broad data set," says Ganguly, "it will be faster and more efficient at interpreting what it finds when OrganiCam does go into space."

In the meantime, there is plenty that OrganiCam can do here on Earth. Any situation needing chemical analysis where space and volume are constrained—caves, bore holes, tunnels, places where people can't easily go—could benefit. OrganiCam is just 7.5 inches long and 2 inches tall, so aboard a vehicle about the size



of a shoebox—either a drone or a rover—it could take very good measurements quite quickly.

Another earthly application would be clean-room validation. OrganiCam is far too sensitive to be used in most places where humans are, but the rooms where Mars rovers and other space-bound instruments are assembled need to be absolutely free of biological contamination, lest they carry it to their destinations. Currently, clean rooms and their products are monitored by swab-and-culture methods, which can take days to complete.

# JUPITER AND SATURN BOTH HAVE ICY MOONS WITH SIGNS OF LIQUID WATER OCEANS BENEATH THEIR ICY CRUSTS.

OrganiCam can scan a room and identify biological contamination instantly.

Finally, although evidence exists of water and organic molecules on Mars, that isn't the only enticing locale where OrganiCam could work. Jupiter and Saturn both have icy moons, Europa and Enceladus respectively, with signs of habitability. Scientists believe that both moons have liquid water oceans beneath their icy crusts. Conveniently, both moons appear to periodically spew out plumes of ocean

contents, which fall back and coat the surface, where they might be examined by an organic-molecule detector.

Whereas life on Mars is thought to be extinct, if it ever existed, the case for these ocean worlds is different. Because they still have liquid water oceans, Europa and Enceladus carry the possibility of extant living organisms in their water. A lander outfitted with OrganiCam could detect them by determining which, if any, organic materials are being spewed out of these subsurface oceans. For many it's a far-out thought, but for the OrganiCam team it's entirely feasible and practically within reach.

"OrganiCam is a revolutionary compact instrument that can detect organic materials here on Earth or discover them on other planets," touts Wiens.

"We're fortunate," adds Sandoval. "It takes a lot of people—from concept people and design people to fabrication people and test people." Luckily, Los Alamos is a place where all these kinds of people come together. LDRD

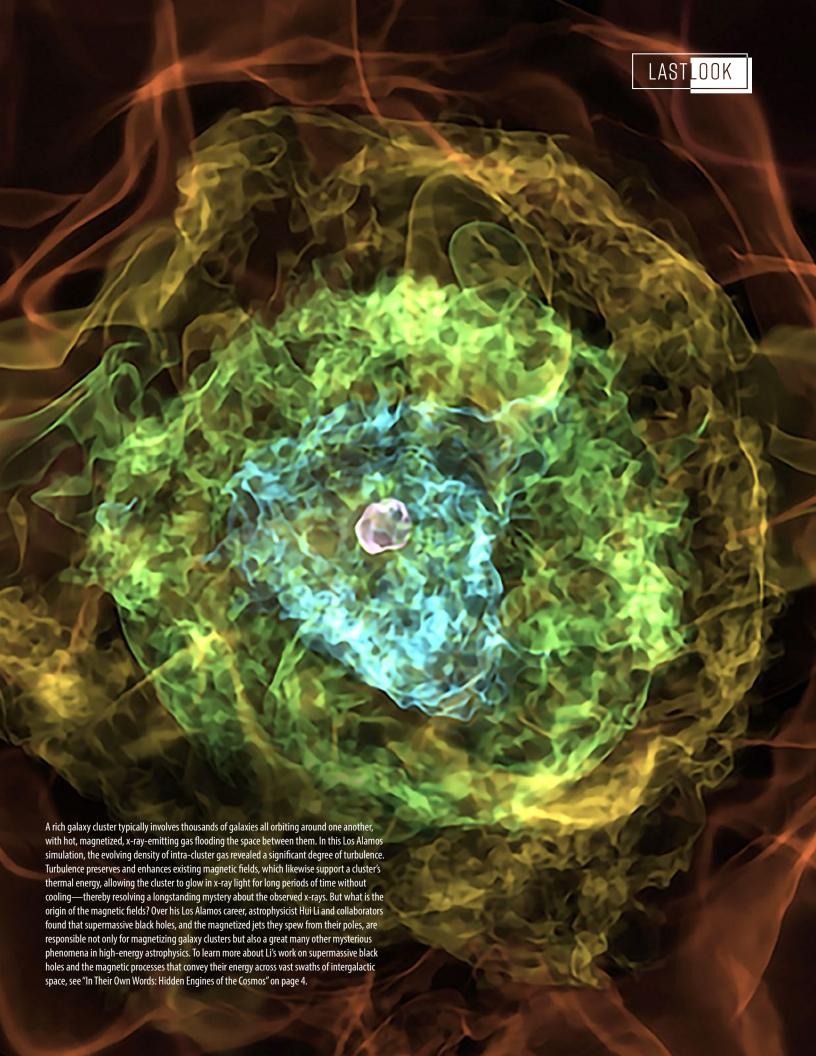
—Eleanor Hutterer

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The Sandia Mountains, home to numerous recreation areas and hiking trails as well as a winter ski area, loom large over Albuquerque, New Mexico, in the Rio Grande river valley below. Albuquerque is the state's largest city with a population of 560,000 and is a 90-minute drive south from Los Alamos.



